

The T2K experience*: Use of near detectors in oscillation analyses

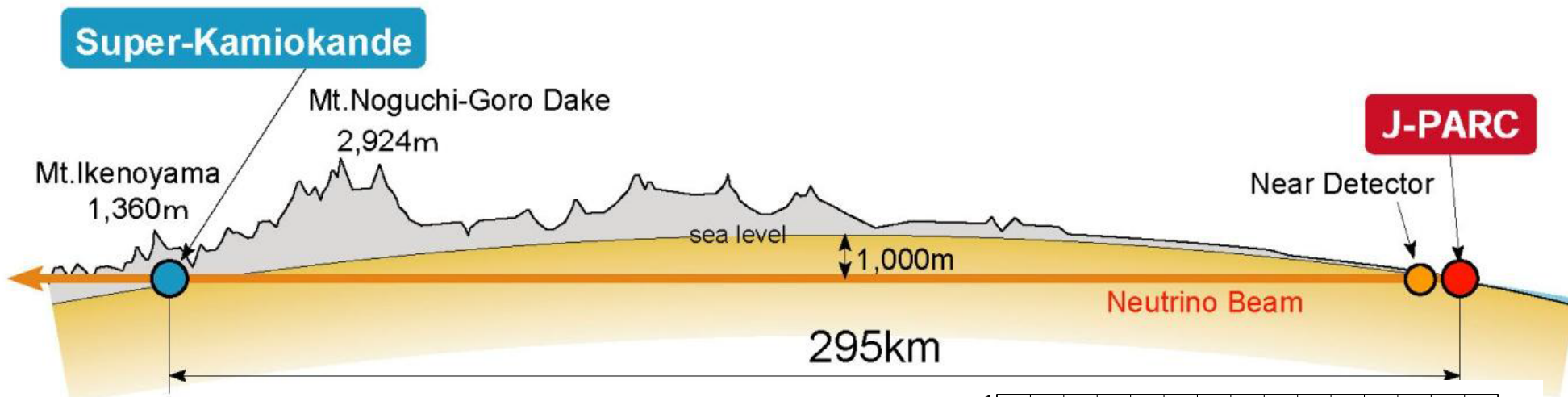
Kendall Mahn
for the T2K collaboration

Michigan State University

**The most fun amusement park ride
you will ever go on!*



The Tokai-to-Kamioka experiment



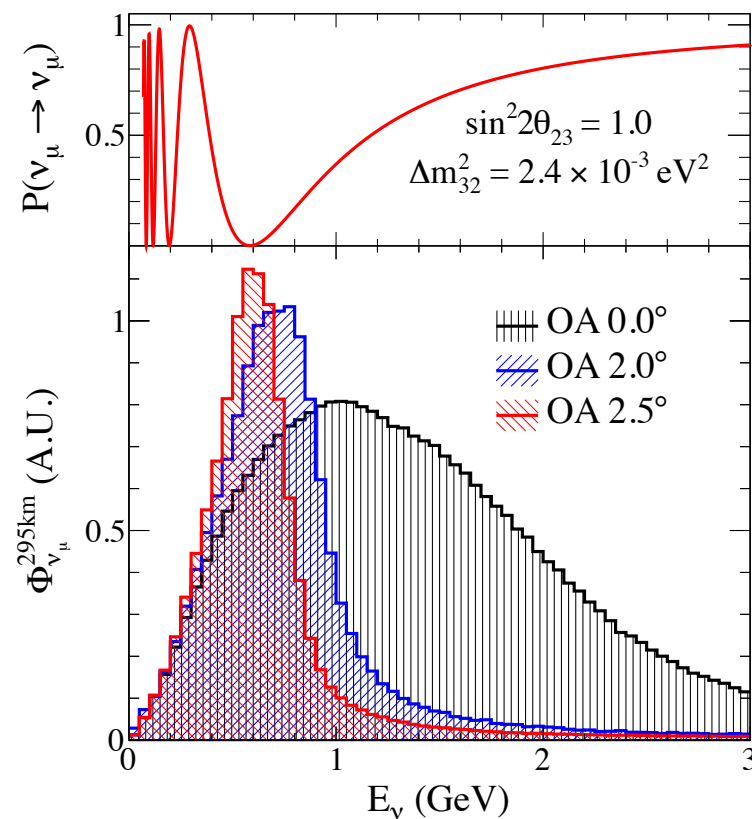
Measurements so far:

ν_μ to ν_e (and $\bar{\nu}_\mu$ to $\bar{\nu}_e$) appearance:

- Discovery of ν_e appearance (2013)
- Search for presence of appearance with antineutrinos; necessary step toward future CPV searches

$\nu_\mu, \bar{\nu}_\mu$ disappearance:

- World's best measurement of θ_{23}
- With antineutrinos: test of NSI or CPT theorem



$$N_{FD} \sim \Phi_{FD}(E_\nu) \sigma(E_\nu) \epsilon_{FD} P(\nu_\mu \rightarrow \nu_e)$$

Fit the observed rate of ν_e or ν_μ to determine the oscillation probability, P . Depends on:

Neutrino
flux
prediction

Neutrino cross
section
model

Far detector
selection,
efficiency

We reduce the error on the rate of ν_μ with the near detector:

$$N_{ND} \sim \Phi_{ND}(E_\nu) \sigma(E_\nu) \epsilon_{ND}$$

Neutrino
flux
prediction

Neutrino cross
section
model

Near detector
selection,
efficiency

$$N_{FD} \sim \Phi_{FD}(E_\nu) \sigma(E_\nu) \epsilon_{FD} P(\nu_\mu \rightarrow \nu_e)$$

Fit the observed rate of ν_e or ν_μ to determine the oscillation probability, P . Depends on:

Neutrino

Neutrino cross

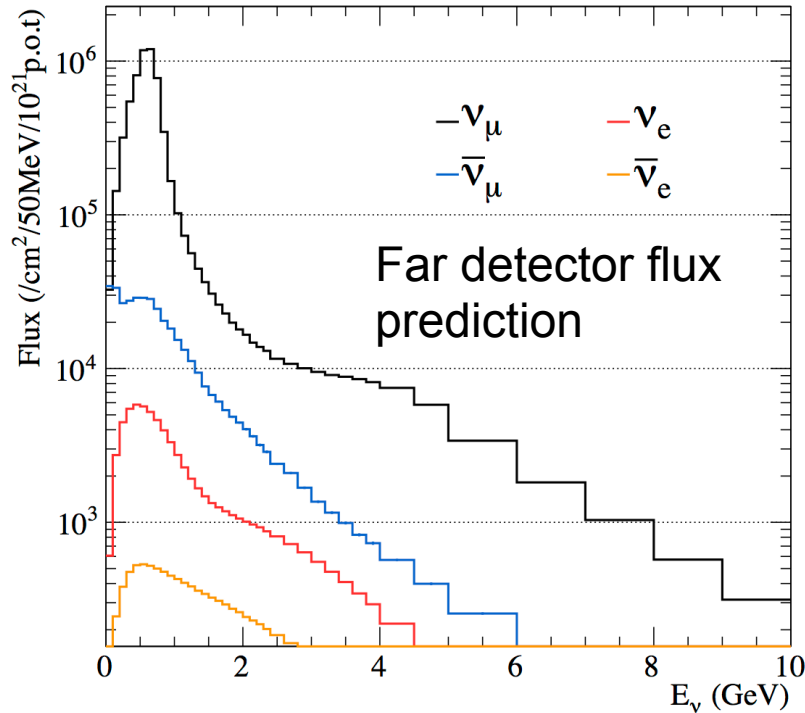
Far detector

T2K's near to far extrapolation has evolved over the last 5 years

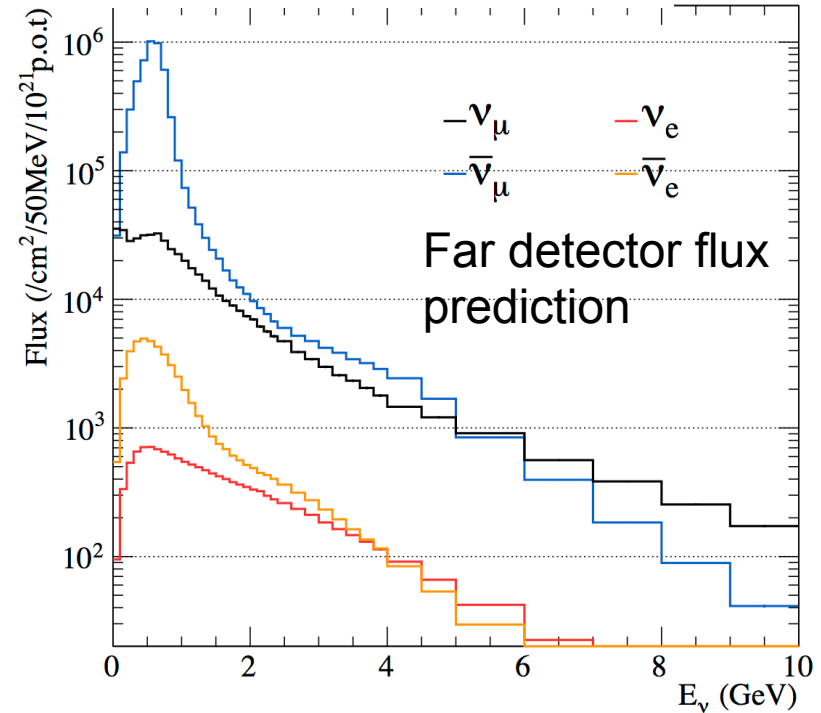
Presentation today will focus on this year's antineutrino analysis and recent improvements to flux, cross section models

Significant background in antineutrino analyses from neutrino interactions motivates inclusion of ND neutrino-mode, antineutrino-mode data sets

Neutrino mode operation

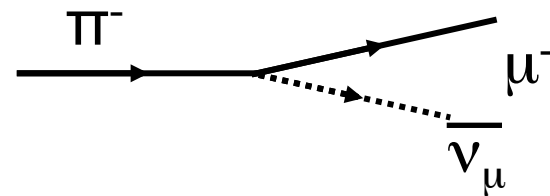
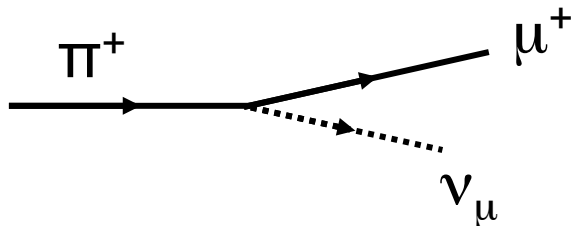


Antineutrino mode operation



FLUKA/Geant3-based neutrino beam simulation (PRD 87, 012001)

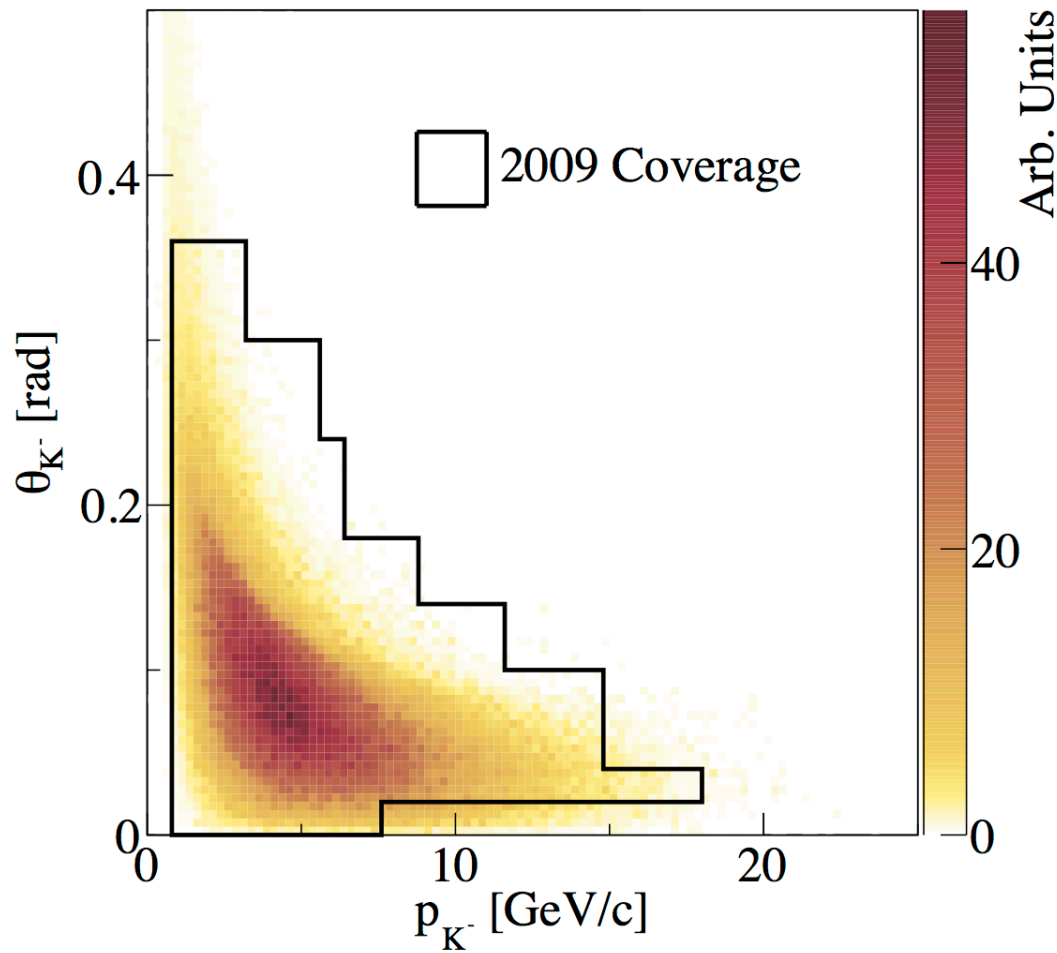
- Significant neutrino component to antineutrino mode beam (“wrong sign” component)



- “Intrinsic” ~0.5% electron (anti)neutrino component

Prediction based on external or in-situ measurements of:

- proton beam (30 GeV)
- alignment and off-axis angle
- $\pi^{+/-}$, $K^{+/-}$ production from NA61

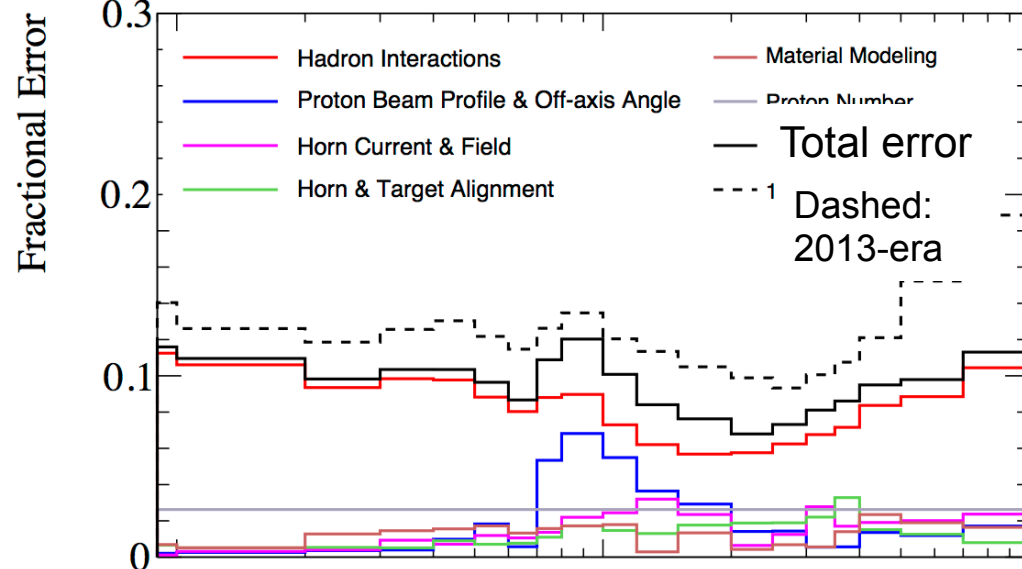


Dedicated hadron-production experiment at CERN

- Thin target data analysed so far, replica target data taken
- Improved results for $\pi^{+/-}$ expand (anti)neutrino production phase space
- New K^- (and K_S^0) measurements
 - K^- : ν_μ production
 - K_S^0 : Intrinsic ν_e production

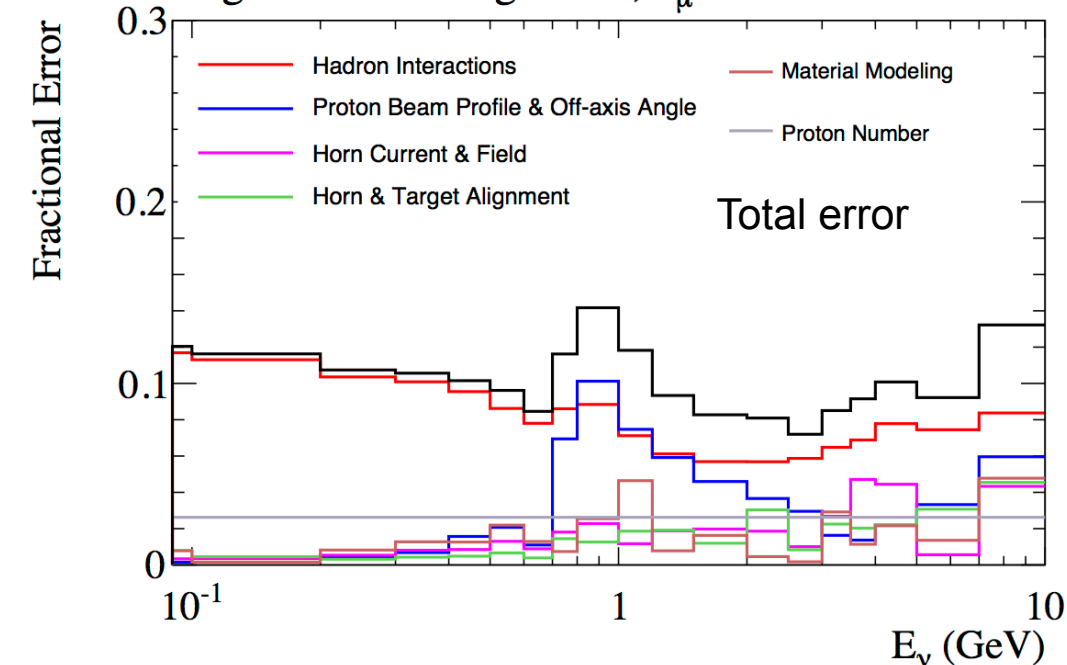
*See A. Bravar's talk (NA61 pion analysis) joint WG1,4 talk
Thurs 12-12:30*

SK: Positive Focussing Mode, ν_μ

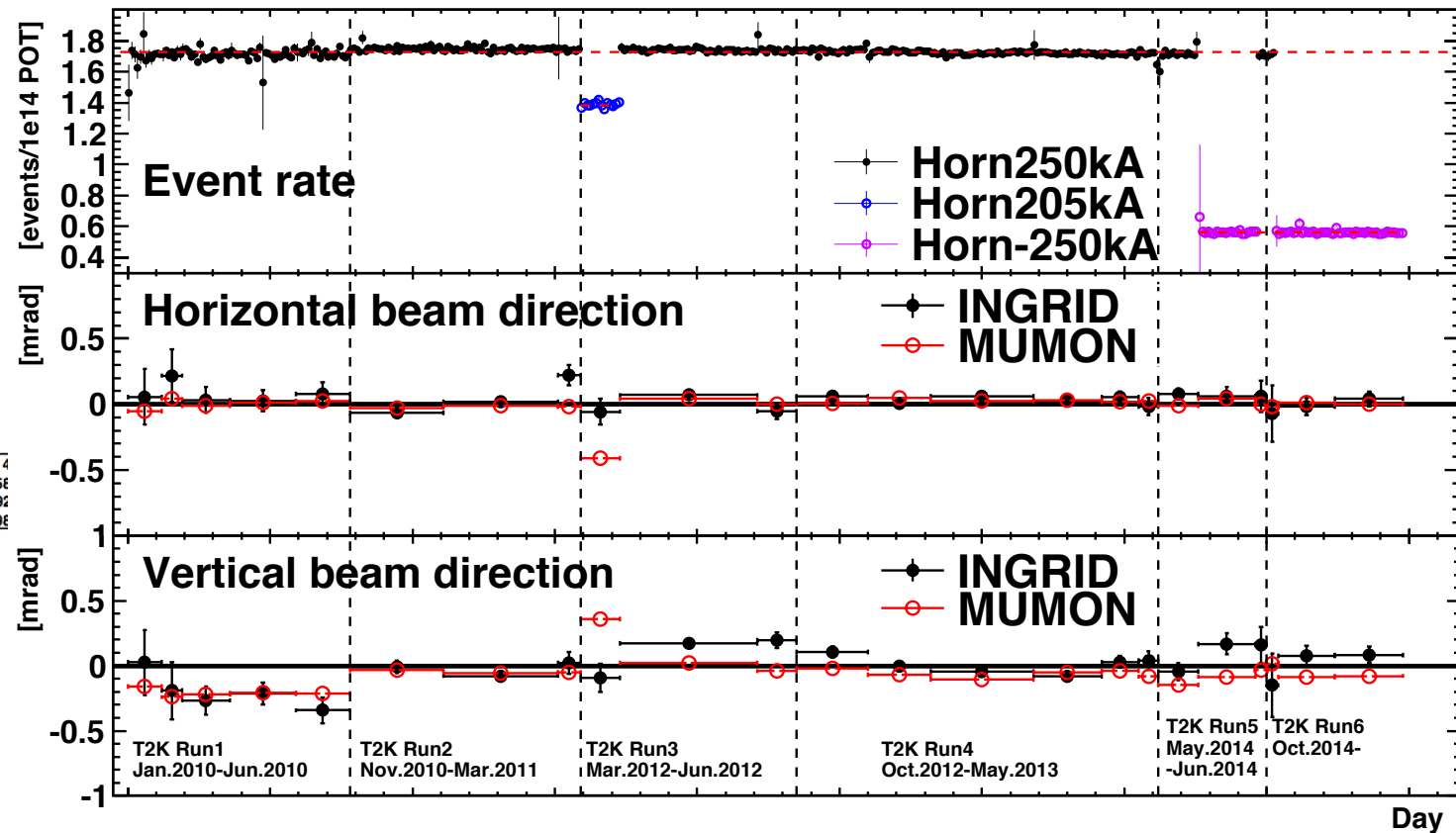
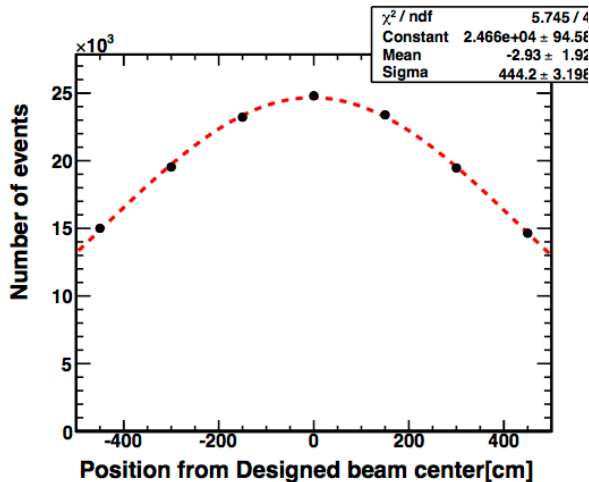
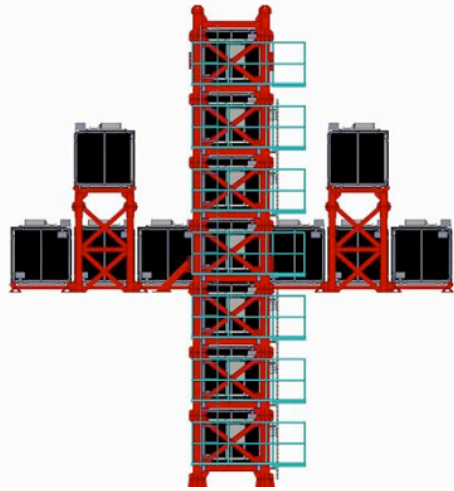


Dominant flux uncertainties are from hadron interactions

SK: Negative Focussing Mode, $\bar{\nu}_\mu$



Uncertainties are comparable for neutrino mode (top) or antineutrino mode (bottom) operation



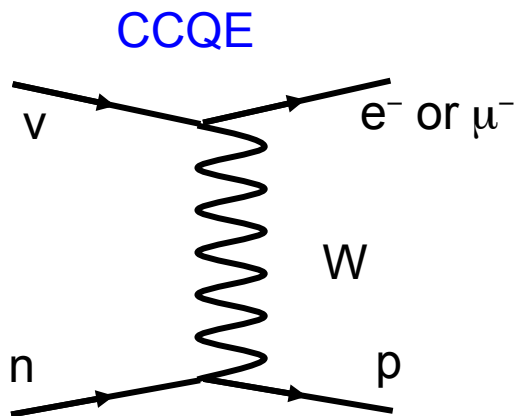
Profile of neutrino beam measured with scintillator/iron detectors placed from 0-0.9 degrees off-axis (INGRID)

- Confirms POT normalized event rate stable (better than 1%)
- Beam direction is stable to within 1mrad; 1mrad corresponds to a 2% shift to peak of the off-axis neutrino energy distribution

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E} \right) + \dots$$

Oscillation probability depends on neutrino energy

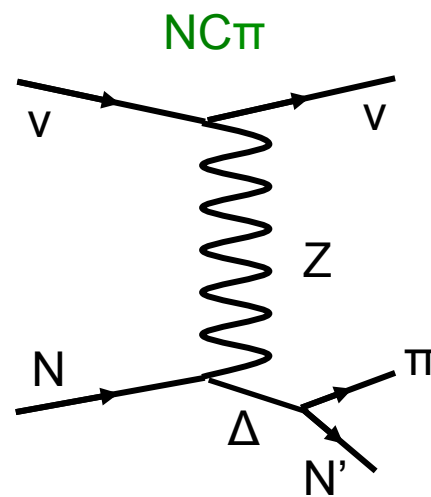
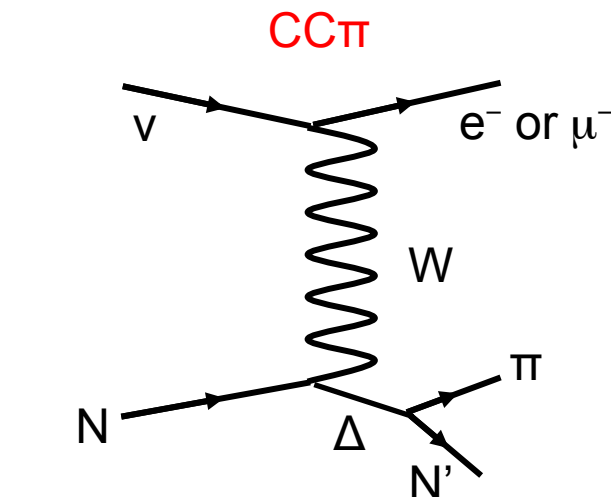
For T2K's neutrino spectrum, dominant process is Charged Current Quasi-Elastic:



Infer neutrino properties from the lepton momentum and angle:

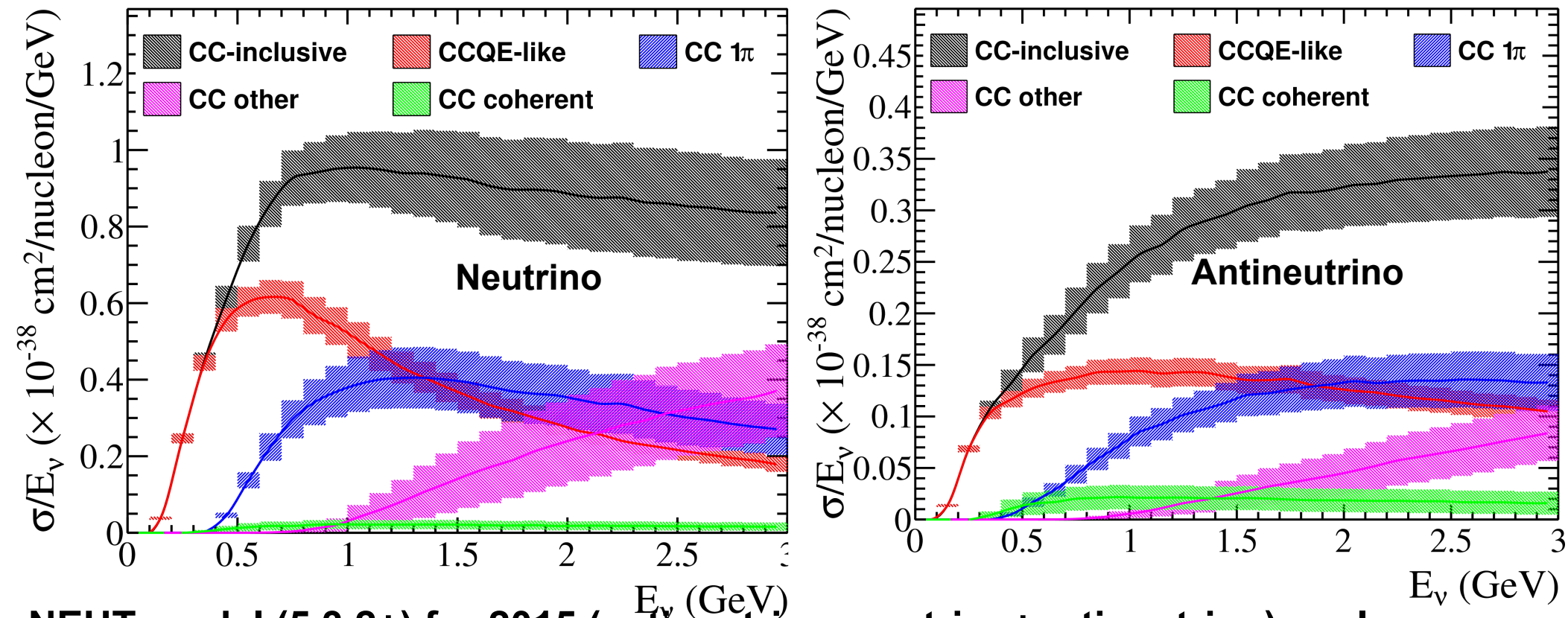
$$E_\nu^{QE} = \frac{m_p^2 - m_n'^2 - m_\mu^2 + 2m_n' E_\mu}{2(m_n' - E_\mu + p_\mu \cos \theta_\mu)}$$

2 body kinematics and assumes the target nucleon is at rest



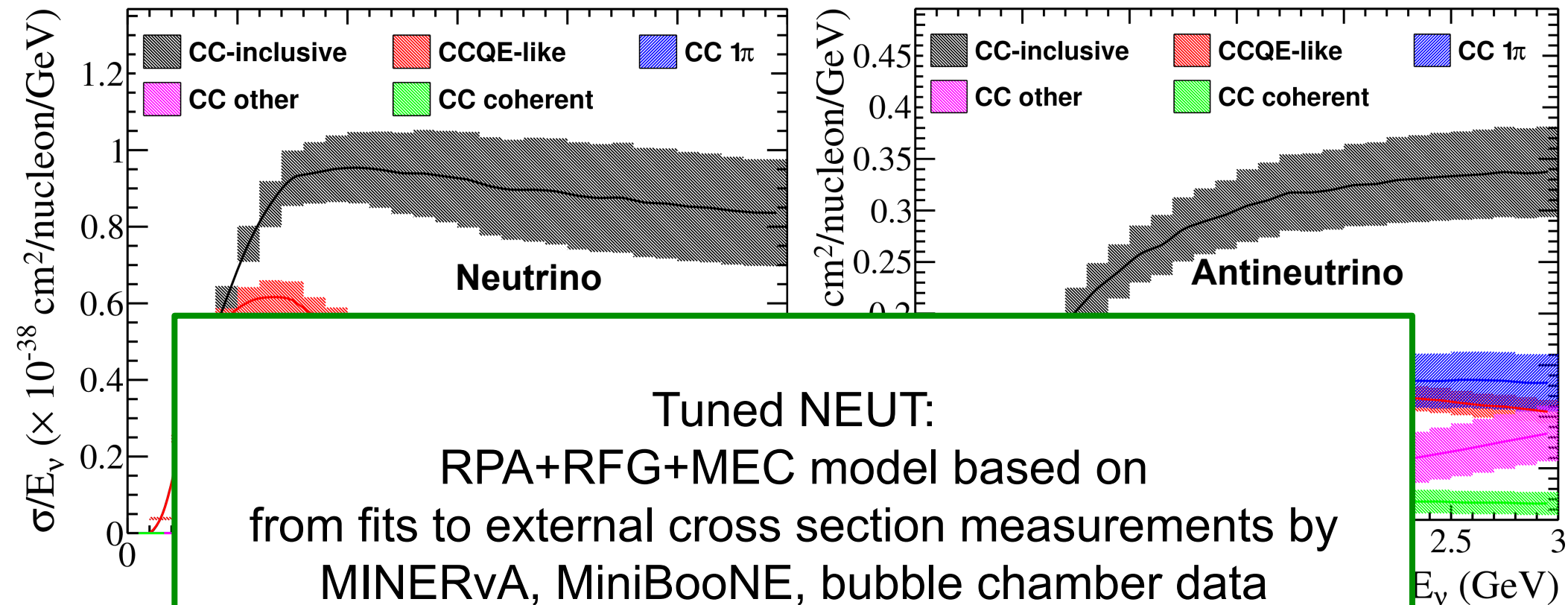
Additional significant processes:

- CCQE-like multinucleon interaction
- Charged current single pion production (CCπ)
- Neutral current single pion production (NCπ)



NEUT model (5.3.2+) for 2015 (antineutrino, neutrino+antineutrino) analyses:

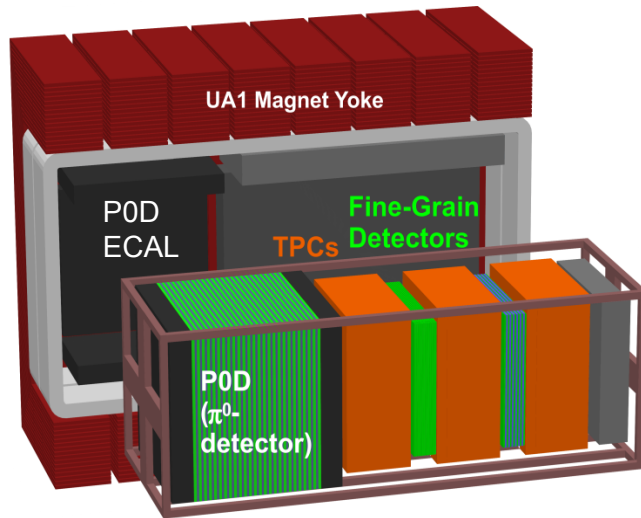
- Two new CCQE models implemented for consideration in the analysis:
 - CCQE: Spectral function model (Benhar et al.) $M_A^{\text{QE}} = 1.2 \text{ GeV}$
 - CCQE: Relativistic Fermi Gas (RFG)+Random Phase Approximation (RPA)
 - New: “Meson exchange current” (MEC) CCQE like scattering from Nieves et. al
- 1 π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta.
No pion-less delta decay.



NEUT model

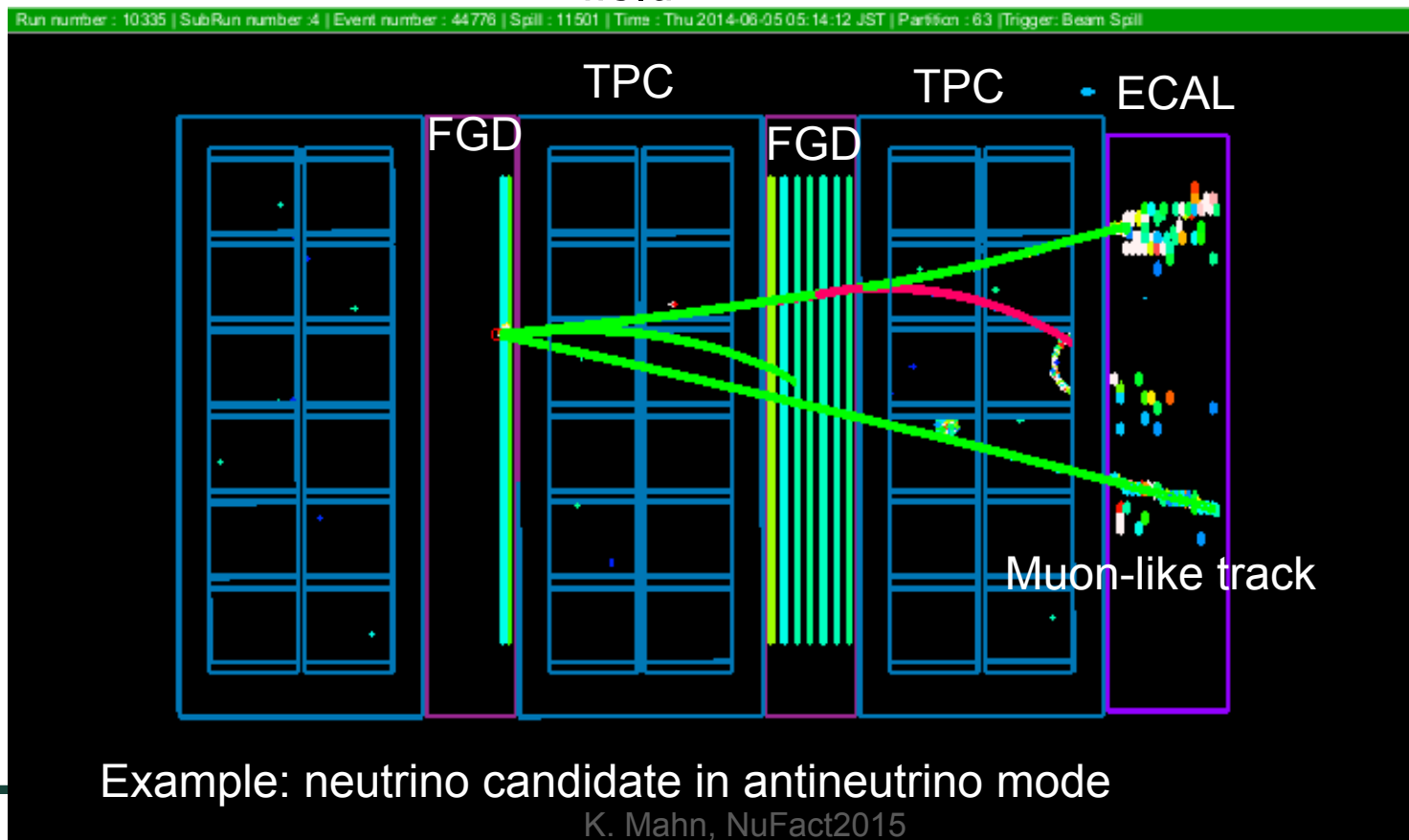
- Two models:
 - CCQE-like
 - CC 1π
- New: “Meson exchange current” (MEC) CCQE like scattering from Nieves et. al
- 1π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.

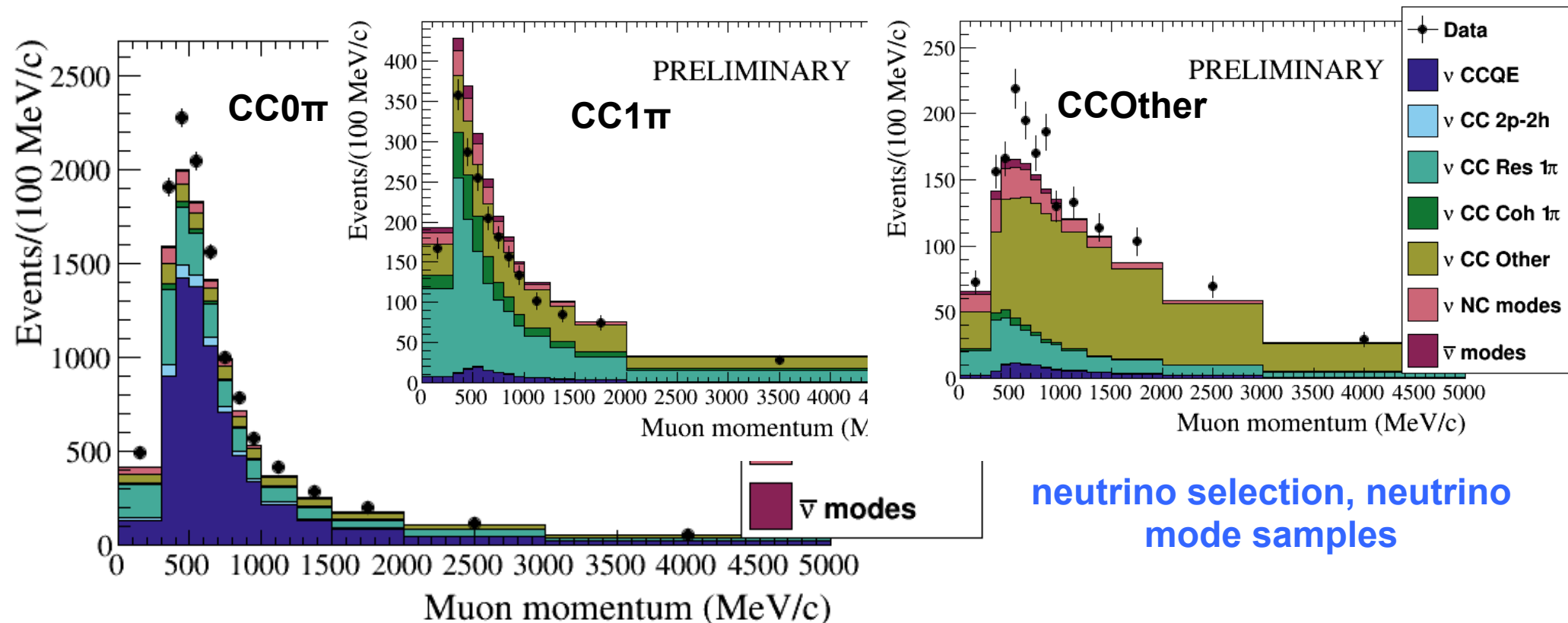
T2K off-axis near detectors: ND280



Select CC ν_μ , $\bar{\nu}_\mu$ candidates prior to oscillations in an off-axis tracking detector (ND280)

- Neutrino interacts on scintillator or water target in tracking detectors (FGDs), muon tracked through scintillator and TPCs
- Additional scintillator (P0D, SMRD) and calorimeters (ECAL)
- Muon momentum, sign from curvature in magnetic field





Select CC ν_μ candidates based on interactions with μ^- :

- Select highest momentum track with negative charge, and PID consistent with a muon

Event samples provide information on flux, cross section model

- Separated based on presence of charged pion in final state (CC0 π , CC1 π , CC Other)
- Pions identified using track multiplicity, dE/dX in TPCs photons in ECALs

ND280 data samples: antineutrino mode

Select CC $\bar{\nu}_\mu$ candidates based on interactions with μ^+ :

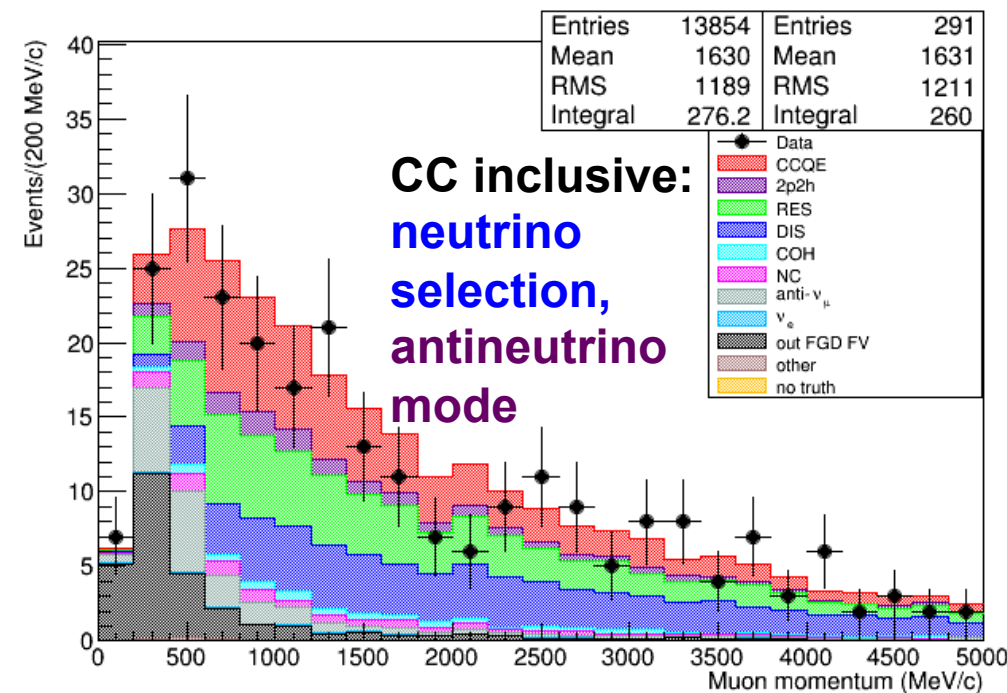
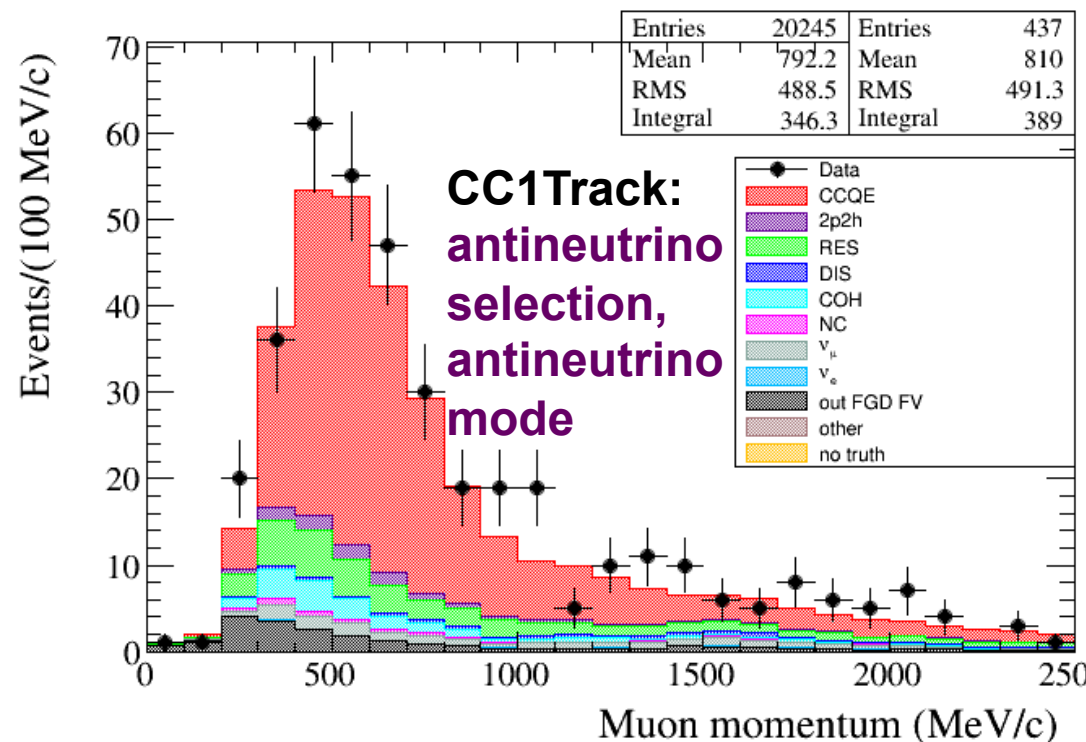
- Select highest momentum track with positive charge, and PID consistent with a muon
- Two sub-samples based on track multiplicity: CC1-Track, CC>1 Track

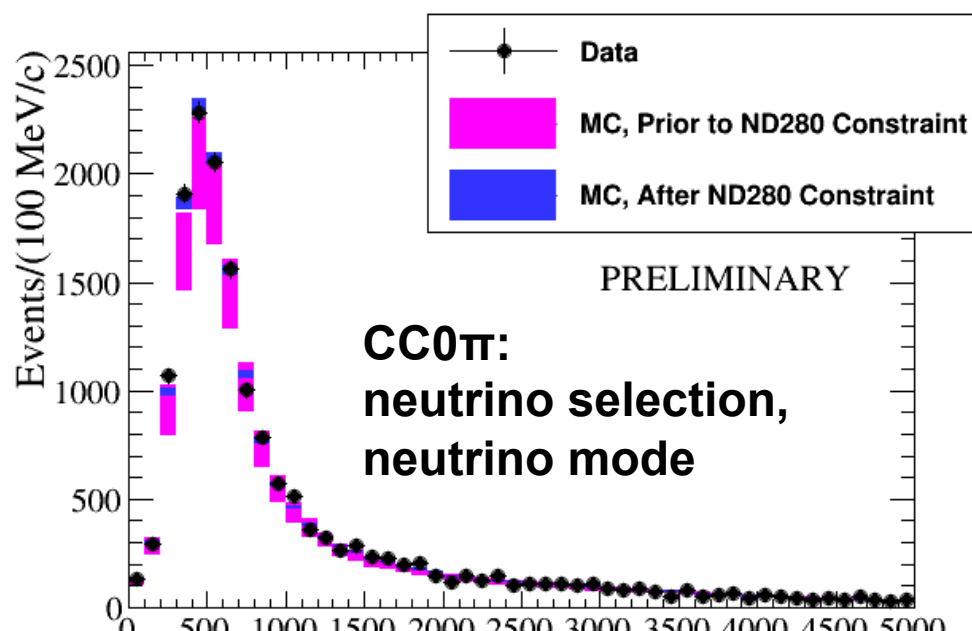
Complementary selection of neutrino candidates in antineutrino mode

Include in fit:

neutrino mode neutrino selections

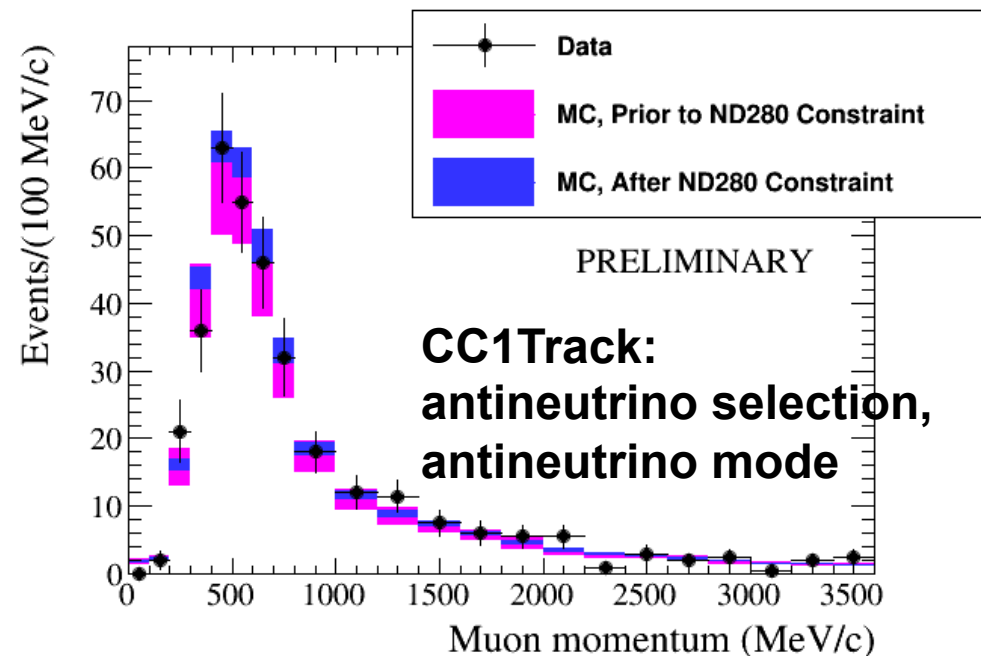
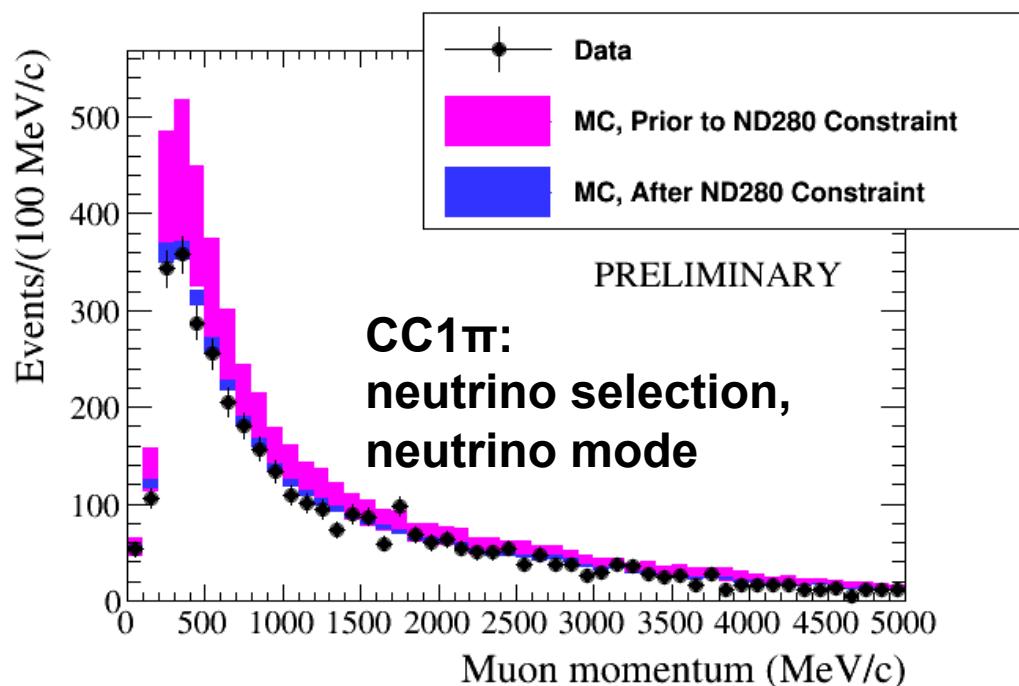
antineutrino mode neutrino and antineutrino selections





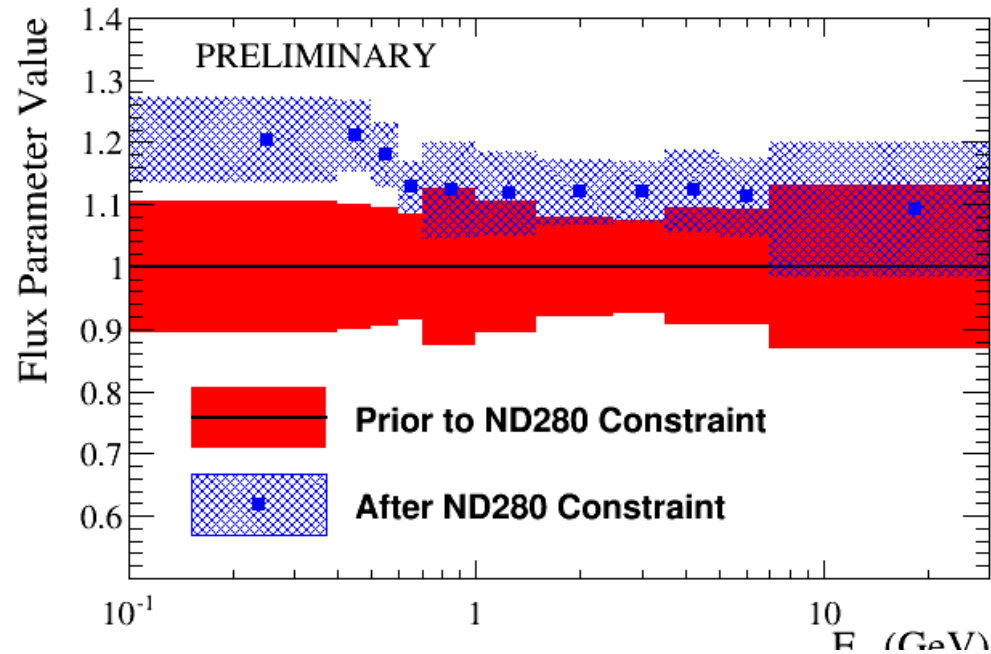
Expected number of events at the far detector is tuned using a likelihood fit to the near detector samples

- Fits include ND detector uncertainties
- Flux and cross section model parameters modified

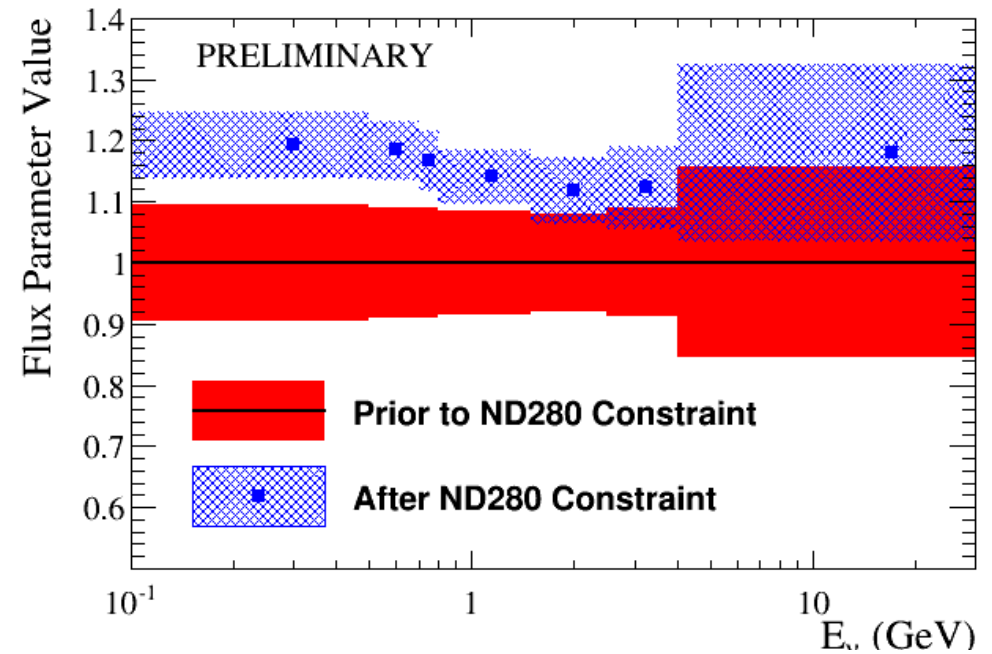


Flux tuning from near detector fit

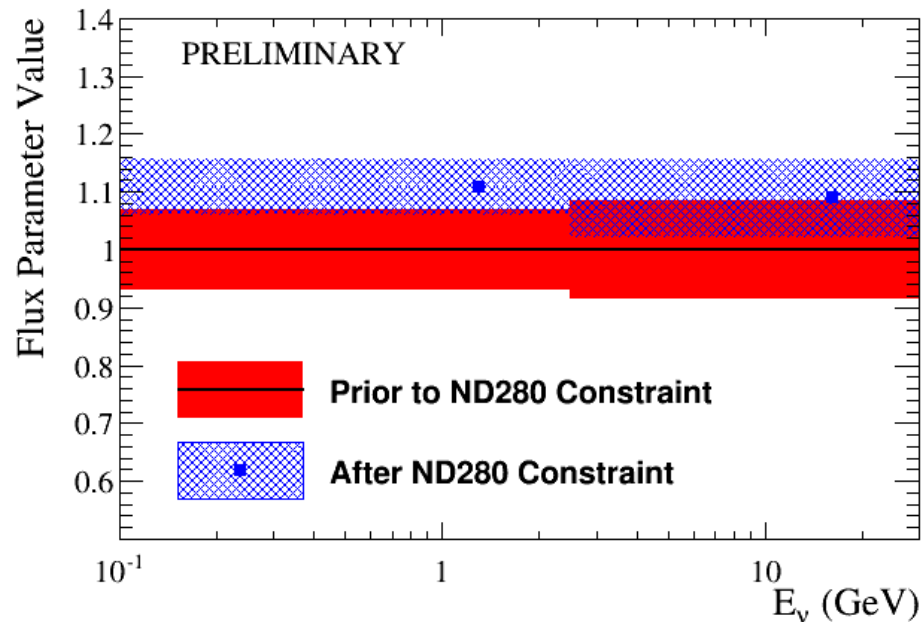
SK $\bar{\nu}_\mu$, $\bar{\nu}$ beam mode



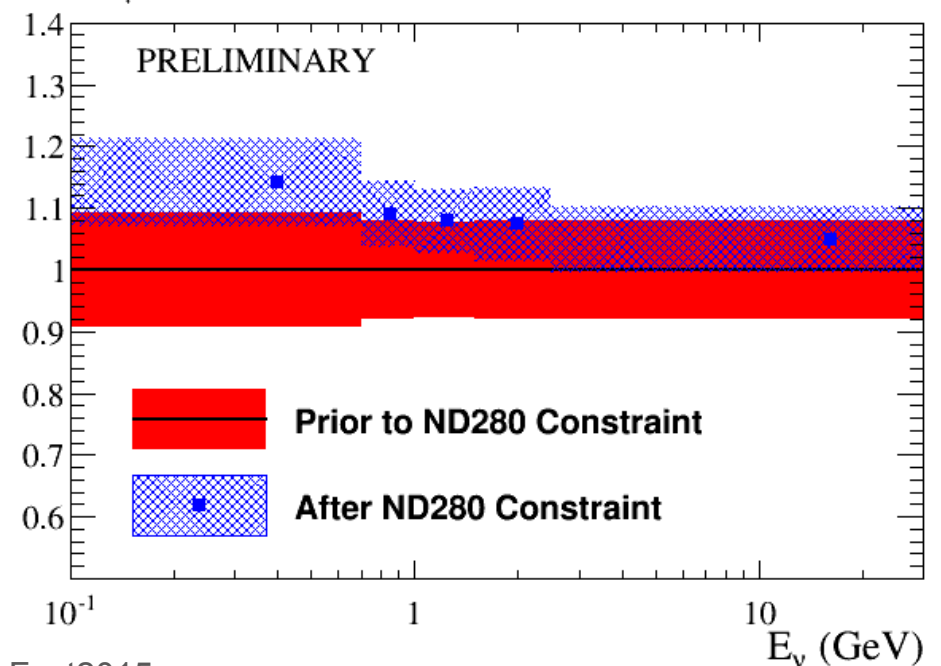
SK $\bar{\nu}_e$, $\bar{\nu}$ beam mode



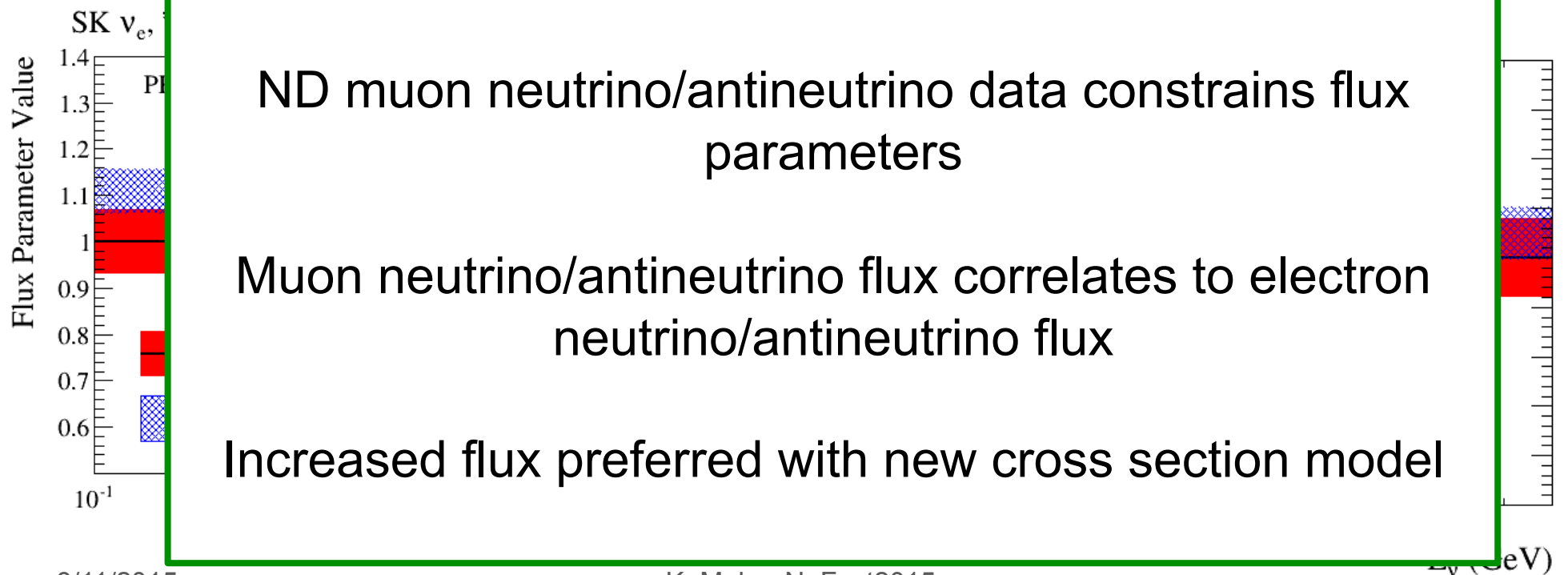
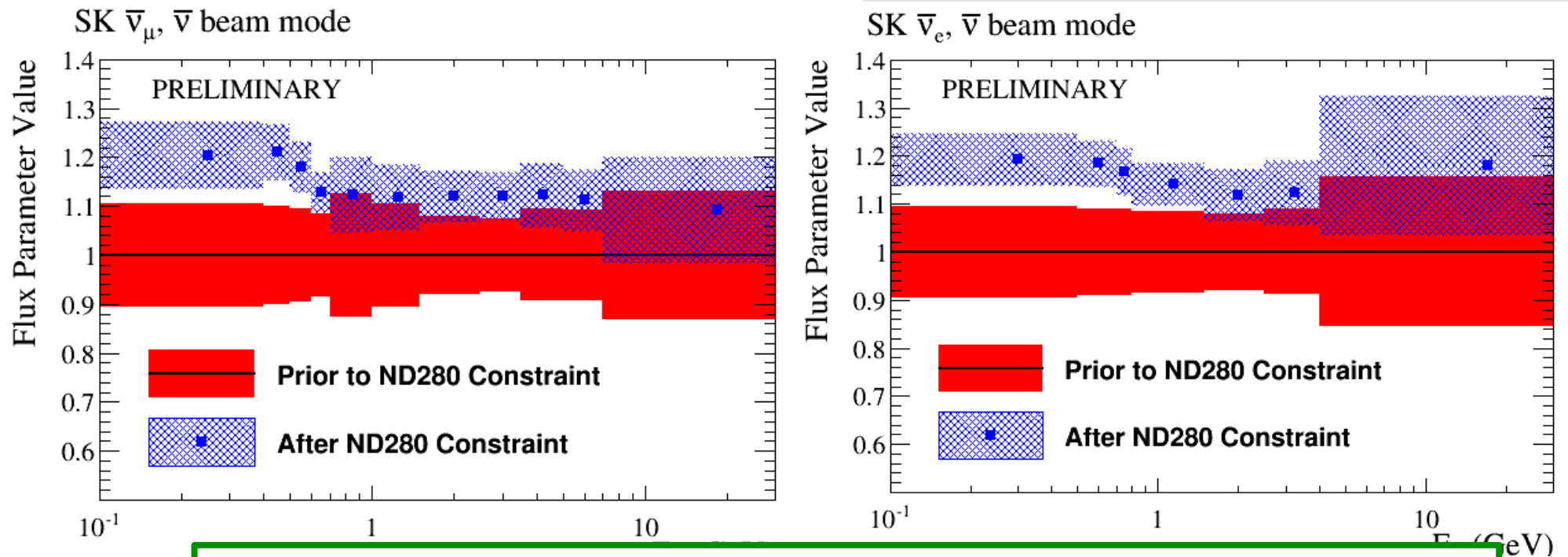
SK ν_e , $\bar{\nu}$ beam mode



SK ν_μ , $\bar{\nu}$ beam mode



Flux tuning from near detector fit

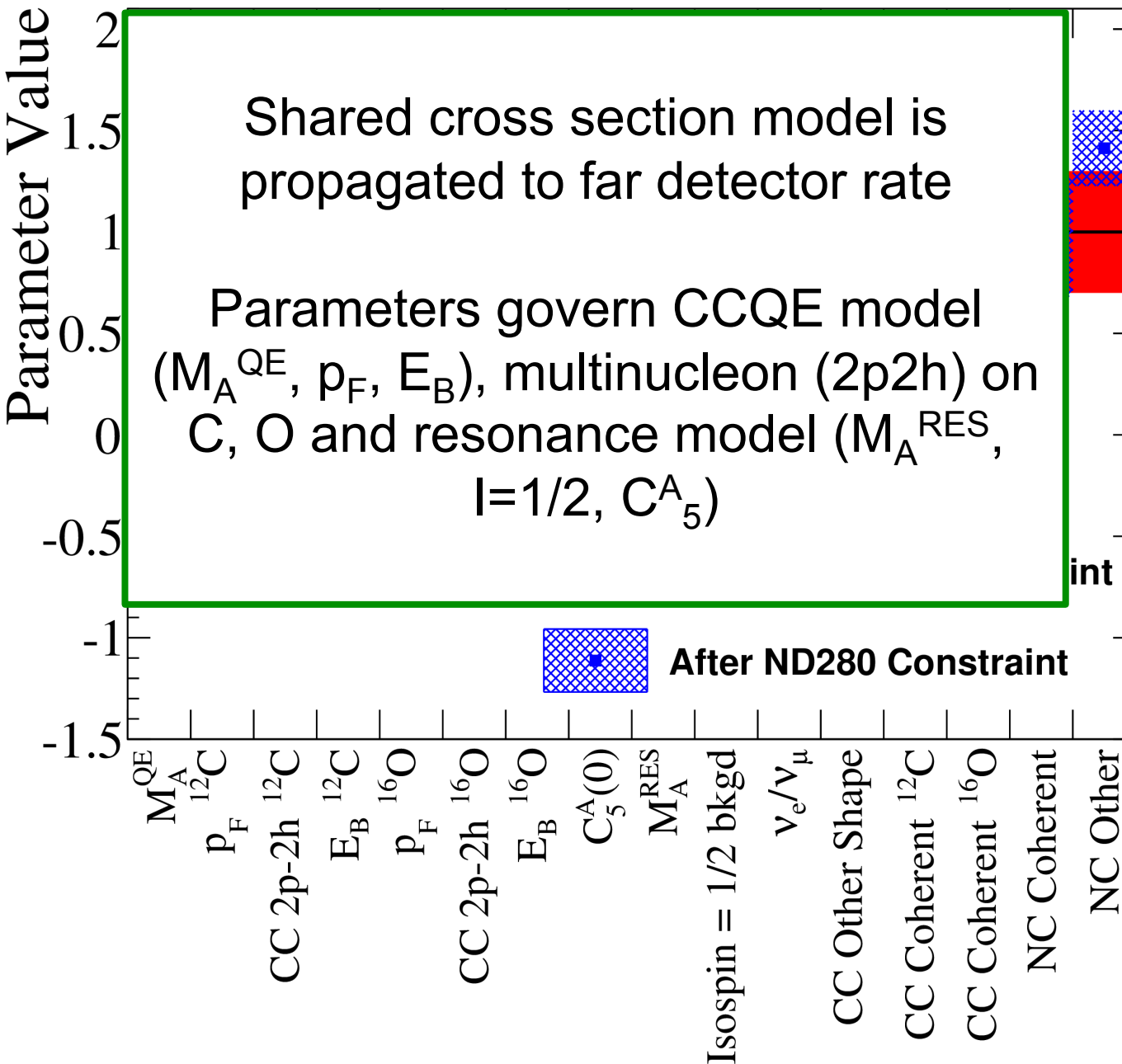


ND muon neutrino/antineutrino data constrains flux parameters

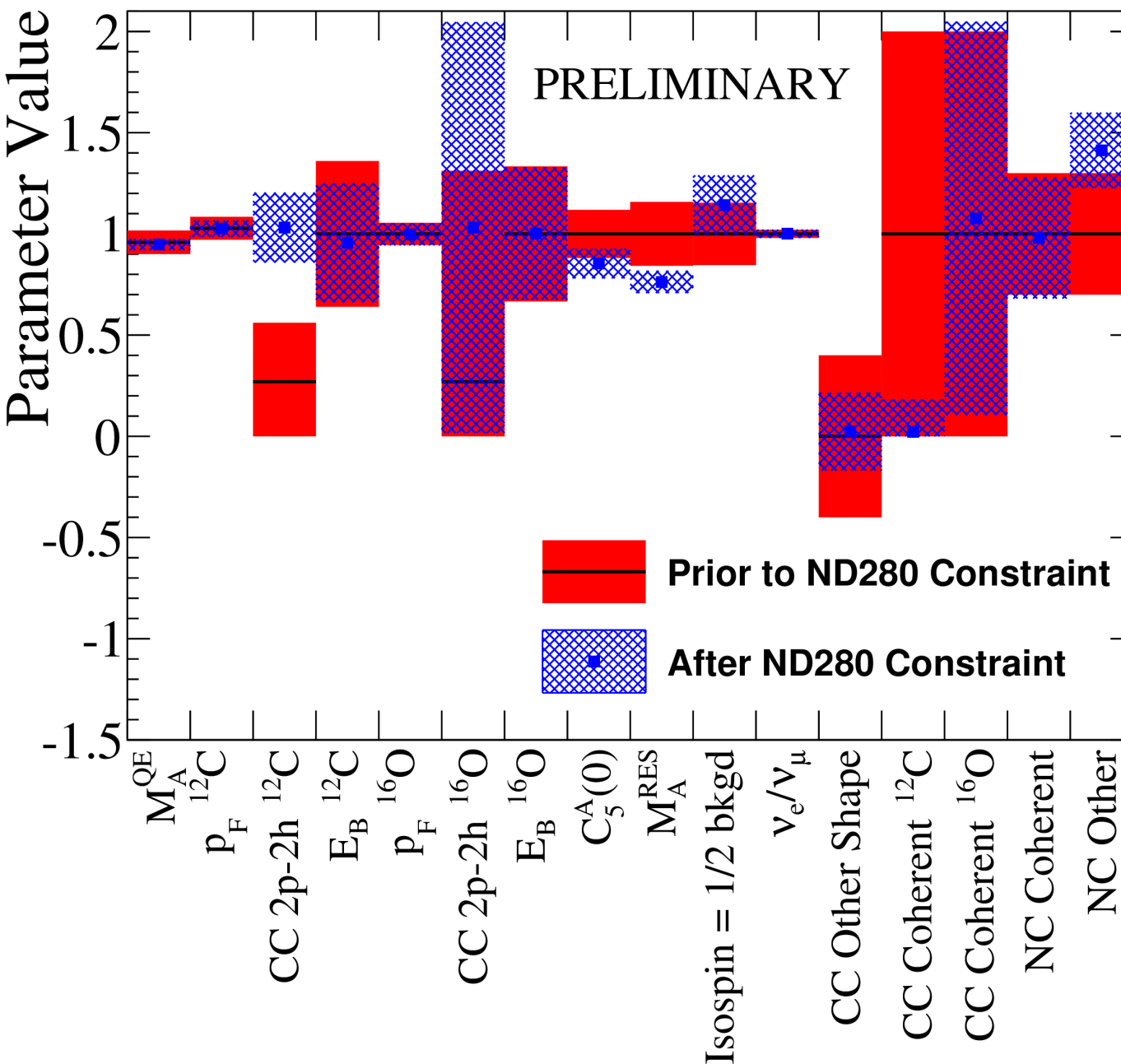
Muon neutrino/antineutrino flux correlates to electron neutrino/antineutrino flux

Increased flux preferred with new cross section model

Cross section tuning from near detector fit



Cross section tuning from near detector fit



Some cross section parameters (2p2h on C, M_A^{RES}) changed significantly compared to external data prior

Expected number of events at the far detector is tuned using a likelihood fit to the near detector samples; substantial reduction to overall uncertainty:

$\bar{\nu}_\mu$ disappearance analysis		w/o ND measurement	w/ ND measurement
ν flux and cross section	flux	7.1%	3.5 %
	cross section cmn to ND280	5.8%	1.4 %
	(flux) \times (cross section cmn to ND280)	9.2%	3.4 %
	cross section (SK only, include \downarrow)	10.0 %	
	multi-nucleon effect on oxygen	9.5%	
	total	13.0%	10.1%
Final or Secondary Hadronic Interaction		2.1%	
Super-K detector		3.8%	
total		14.4%	11.6%

Fractional error on number-of-event prediction

*Antineutrino oscillation analyses are statistics limited
Efforts to improve multinucleon oxygen uncertainty with
FGD2 water samples and C-to-O A scaling studies*

Off-axis near detector data is used in oscillation analyses to constrain parameters associated to the flux, cross section model

- Total uncertainty on far detector muon antineutrino candidates reduced from 14% to 11%

On-axis detectors provide a crucial role

- Monitoring of beam stability, off-axis angle variations with neutrino datasets

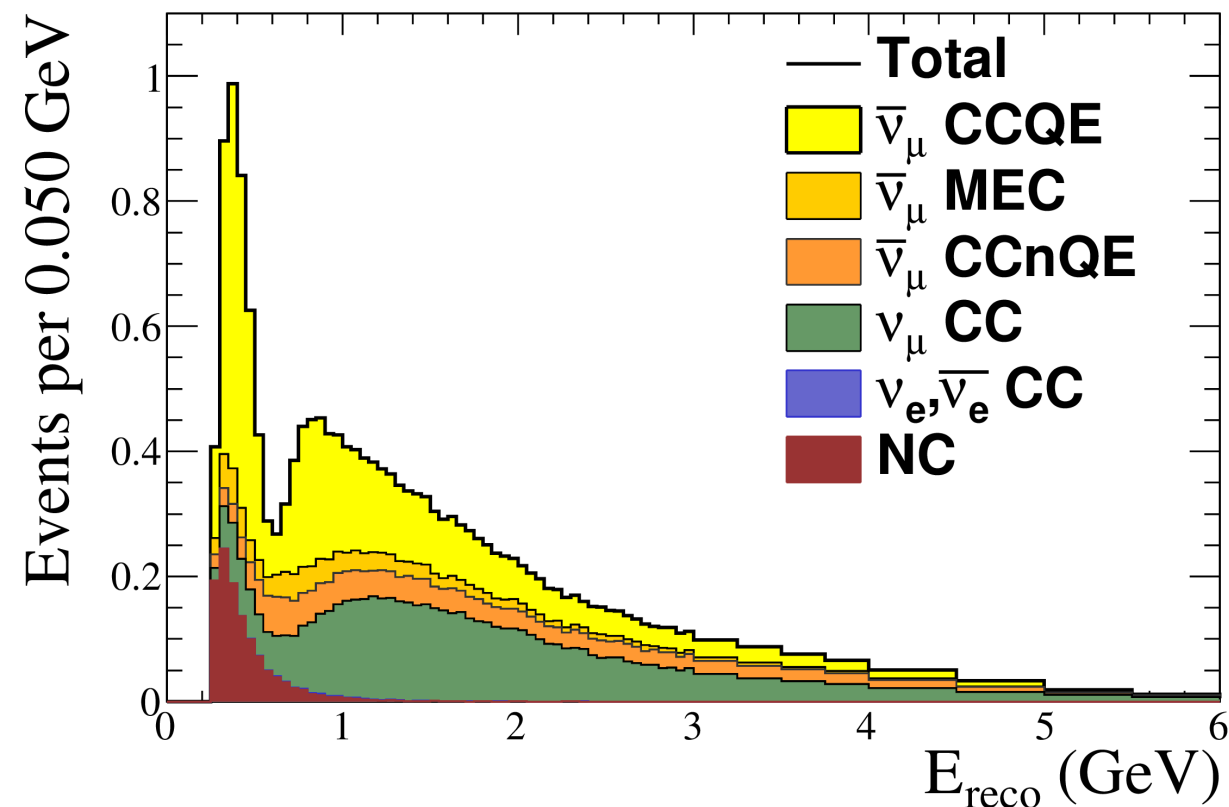
Flux and cross section models, priors are still essential:

- Used to develop a suitable parameterization and extrapolation
- Develop correct physical basis for neutrino, antineutrino mode correlations
- Estimation of significant uncertainties (ν_e/ν_μ cross section, multinucleon oxygen uncertainty)
 - Current ND data sets do not constrain these parameters

Next steps for the T2K near-to-far extrapolation

- Revisit cross section model parameterization
- Include new ND data sets from water-target ND

Backup slides



Predominantly antineutrino interactions, but significant components from other channels

- Expect 34.6 (103.6) events with (without) oscillation

	$\nu_\mu \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
CCQE	6.870	13.258	0.004	0.005	0.007	0.017
MEC	1.578	2.347	0.001	0.001	0.001	0.003
CC1 π	2.414	3.046	0.003	0.002	0.003	0.003
CC coherent	0.167	0.696	0.000	0.000	0.000	0.002
CC other	1.222	0.880	0.001	0.000	0.000	0.000
NC1 π	0.391	0.428	0.016	0.012	-	-
NC other	0.707	0.420	0.035	0.017	-	-
subtotal	13.349	21.076	0.059	0.038	0.011	0.025
total	34.559					

Antineutrino appearance analysis

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	1.961	2.636	3.288	2.481	3.254	3.939
Bkg $\nu_\mu \rightarrow \nu_e$	0.592	0.505	0.389	0.531	0.423	0.341
Bkg NC	0.349	0.349	0.349	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826	0.821	0.821	0.821
Total	3.729	4.315	4.851	4.181	4.848	5.450

Normal hierarchy

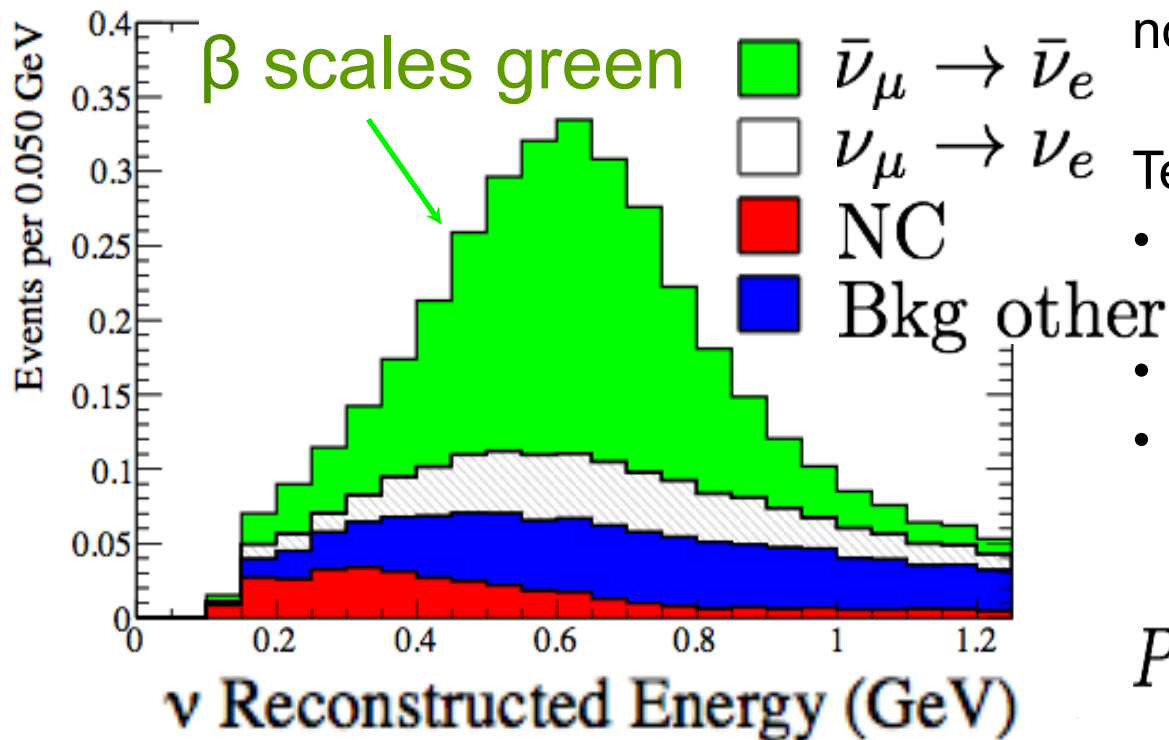
Inverted hierarchy

Expect 3.73 (4.18) events based on normal (inverted) hierarchy

Test of no $\bar{\nu}_e$ appearance hypothesis:

- Significant expected contribution from ν_e appearance
- $\beta=0$: no $\bar{\nu}_e$ appearance
- $\beta=1$: $\bar{\nu}_e$ appearance

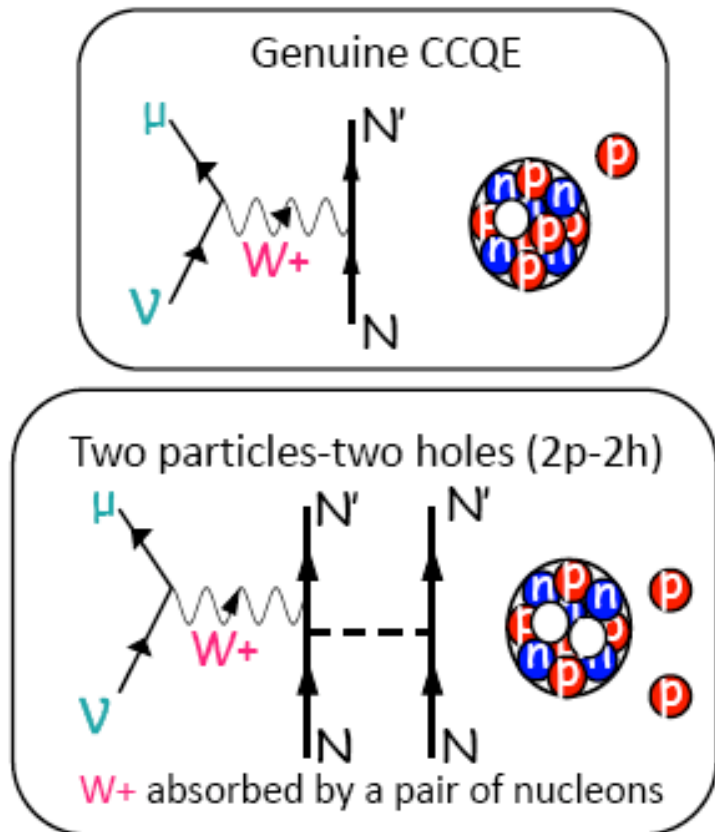
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{\text{PMNS}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



Future systematics: cross section model

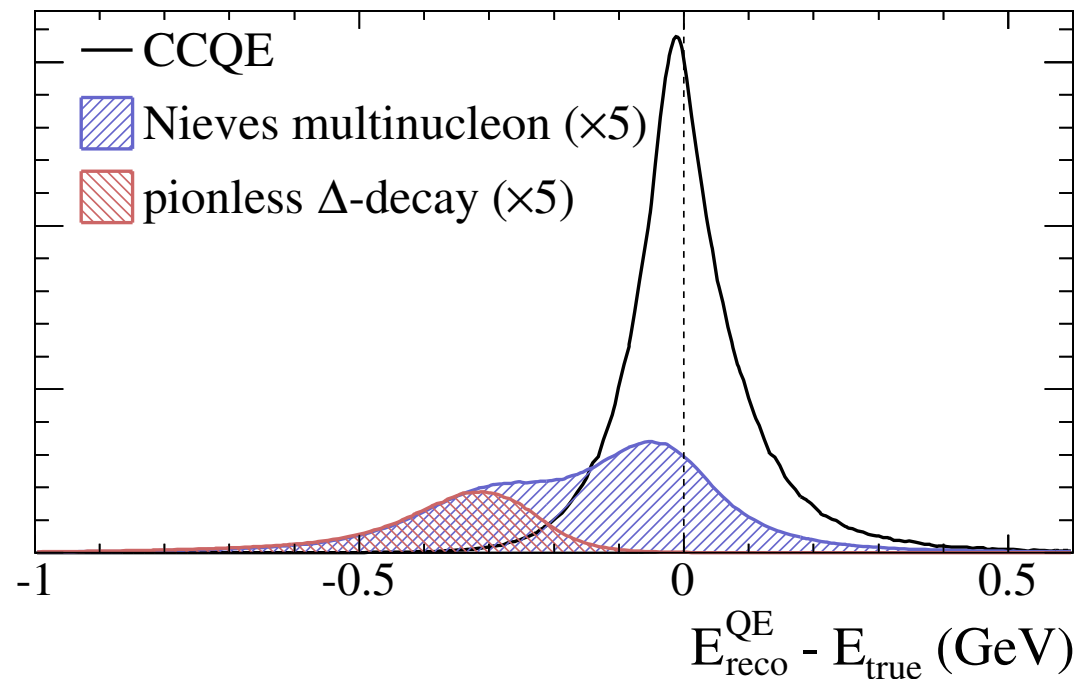
Nuclear effects such as “multinucleon” processes may explain the enhanced CCQE cross section observed by MiniBooNE, SciBooNE experiments

- CCQE interaction simulated as interaction on a single nucleon (1p1h)
- Two models simulate interaction on correlated pair of nucleons (2p2h)
- J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, PRC 83 045501 (2011)
- M. Martini, M. Ericson, G. Chanfray, and J. Marteau, PRC 80 065501 (2009)



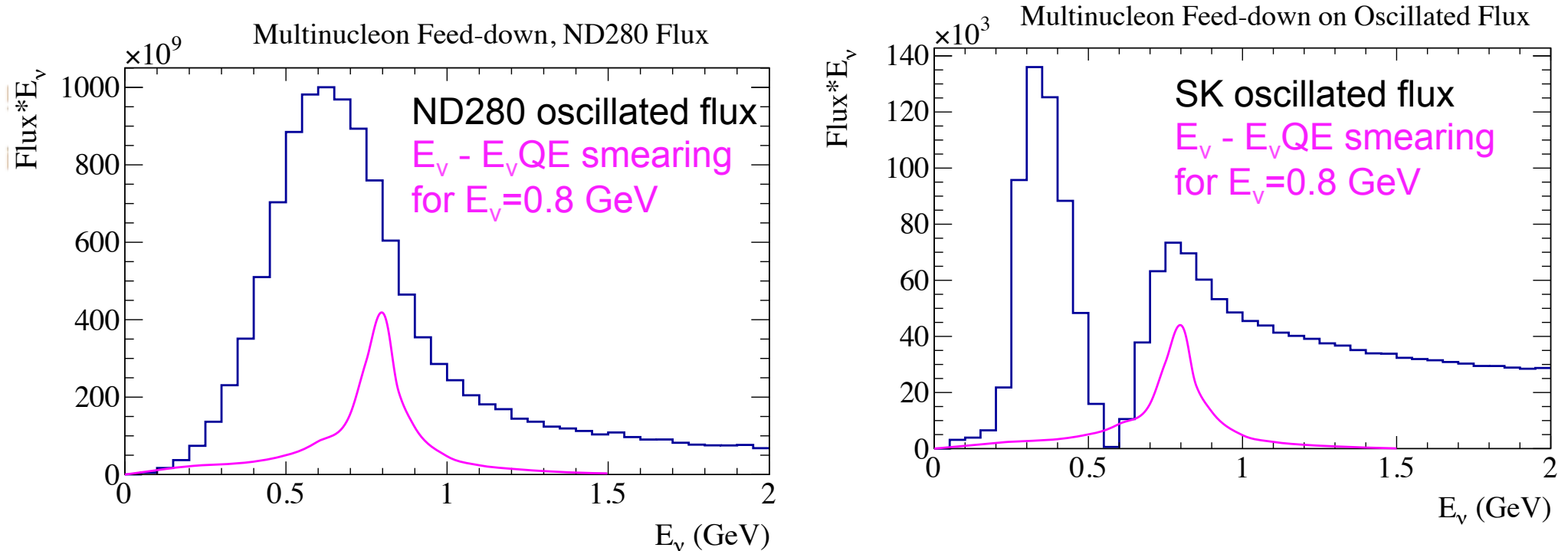
Picture by M. Martini

Arbitrary Units



T2K collab PRL 112, 181801 (2014)

Cross section model couples through the different fluxes measured by ND and FD



$$FD(\nu_e) = \Phi \times \sigma \times \epsilon \times P(\nu_\mu \rightarrow \nu_e)$$

$$ND(\nu_\mu) = \Phi \times \sigma \times \epsilon_{ND}$$

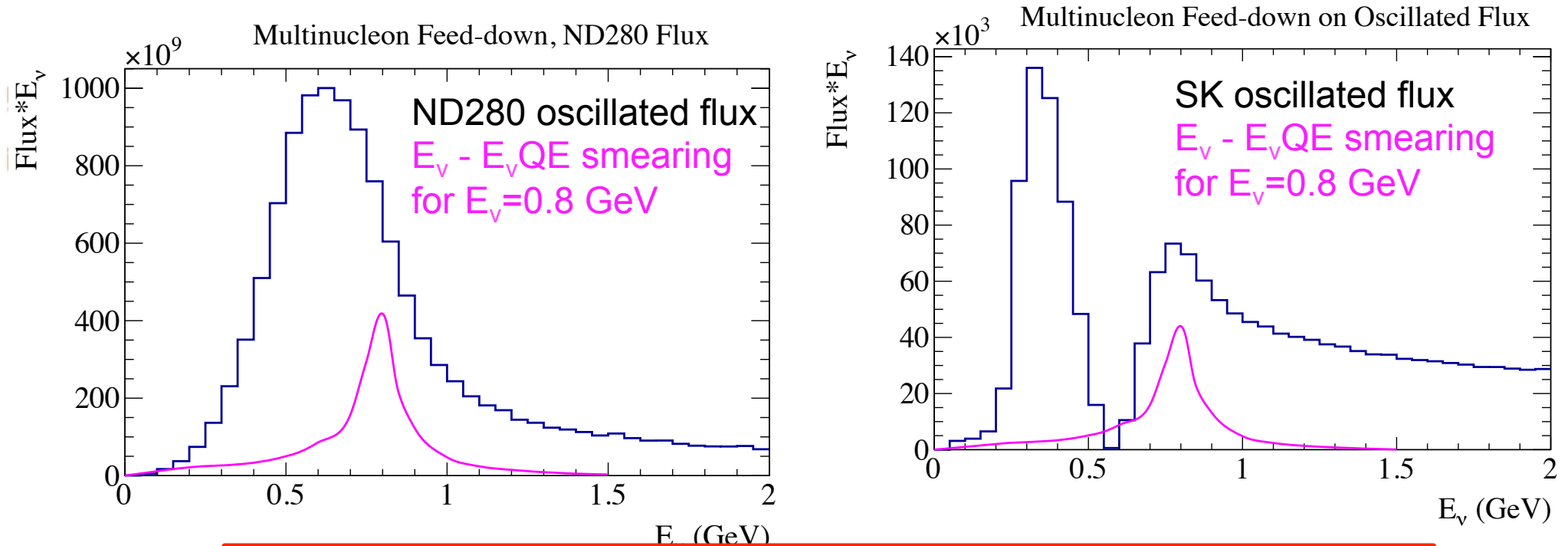
$$E_\nu^{QE} = \frac{m_p^2 - m_n'^2 - m_\mu^2 + 2m_n' E_\mu}{2(m_n' - E_\mu + p_\mu \cos \theta_\mu)}$$

Overall increase to cross section cancels in extrapolation, but any shifts between true to reconstructed E feed down into oscillation dip and are \sim degenerate with θ_{23} measurement

- Similar issue for CC1 π^+ backgrounds where pion is not tagged (absorbed in nucleus or detector)

Future systematics: cross section model MICHIGAN STATE UNIVERSITY

Cross section model couples through the different fluxes measured by ND and FD



$FD(\nu)$

$ND(\nu)$

Overall inc
to reconst
measur

- Similar
nucleus

This effect still occurs even if the near and far detectors are the same technology

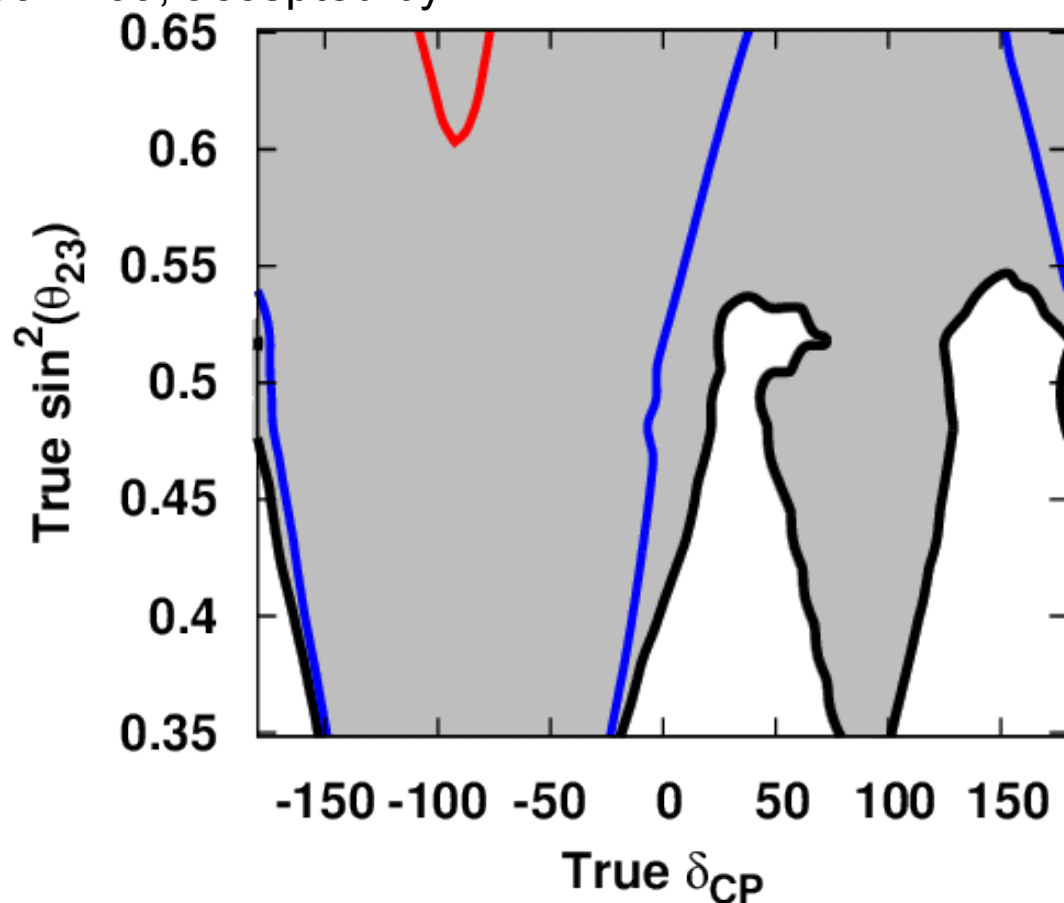
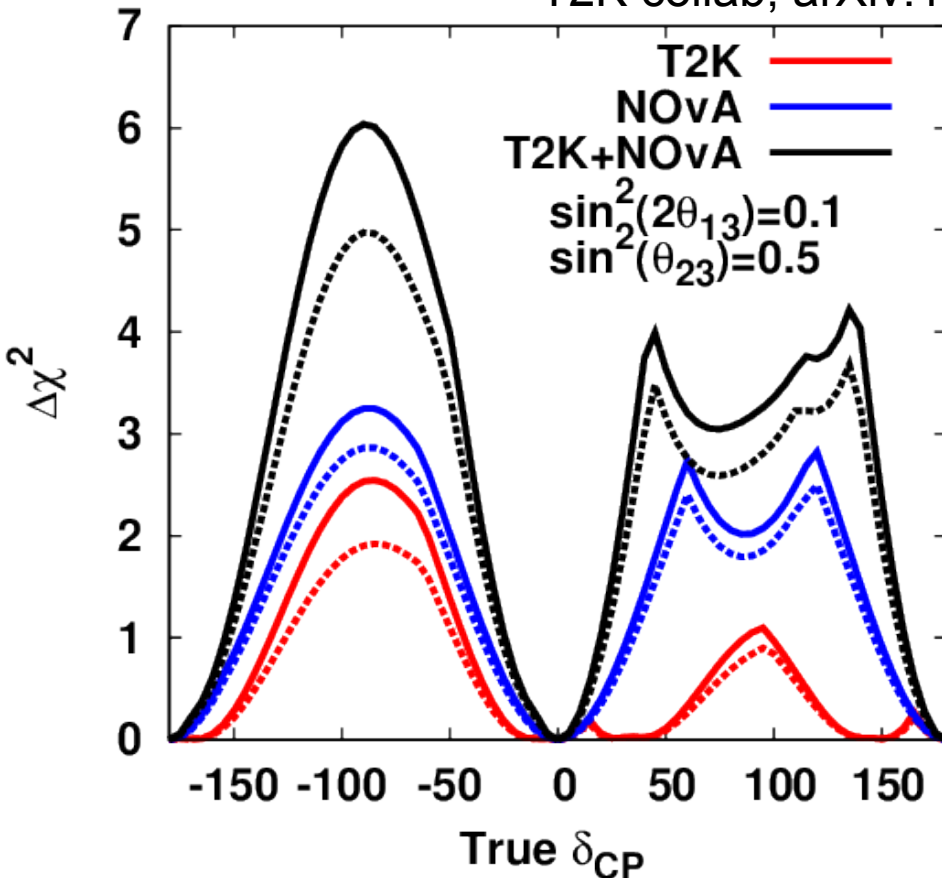
Critical to understand differences between neutrino and antineutrino due to 2p2h/MEC for future measurements

$$\frac{n'_n E_\mu}{s \theta_\mu})$$

een true

in

T2K collab, arXiv:1409.7469, accepted by PTEP



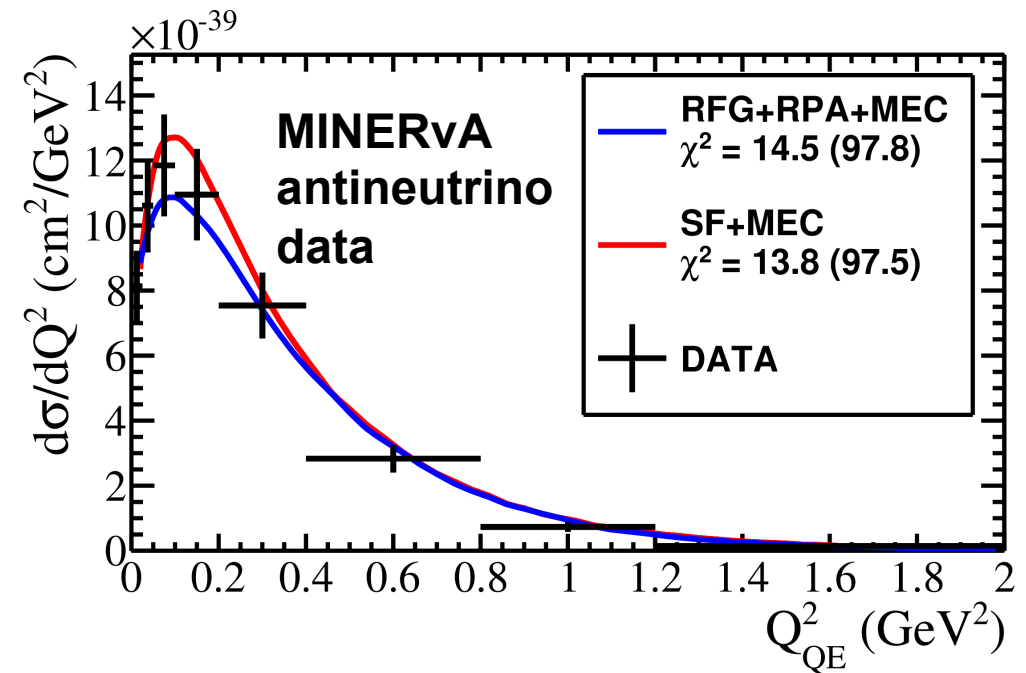
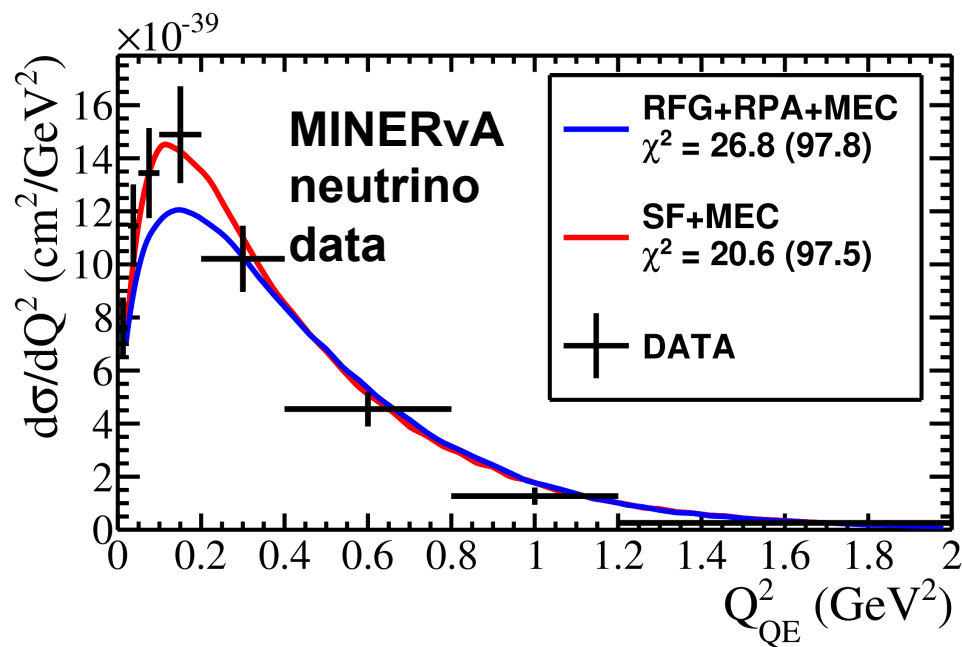
NOvA's higher energy (peak $E_\nu \sim 2$ GeV) and longer baseline ($L \sim 810$ km) has a different dependence on mass hierarchy (MH) through the matter effect

- Gray regions are where the mass hierarchy can be determined to 90% CL for T2K (red), NOvA (blue), and T2K+NOvA (black)

Determination of MH depends on θ_{23}

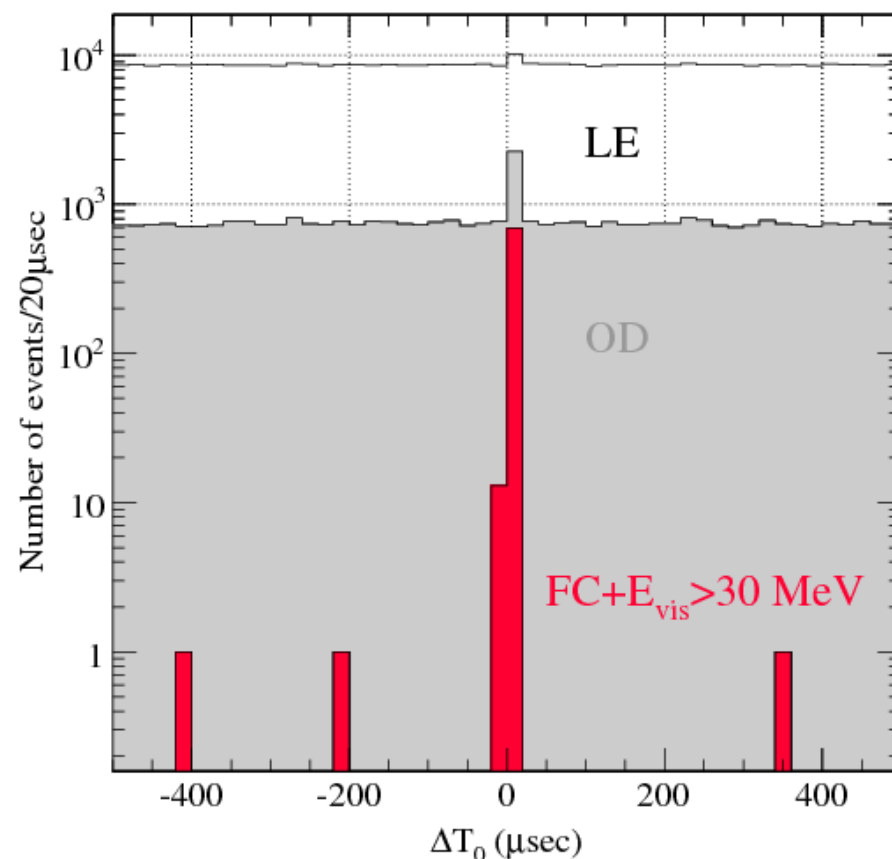
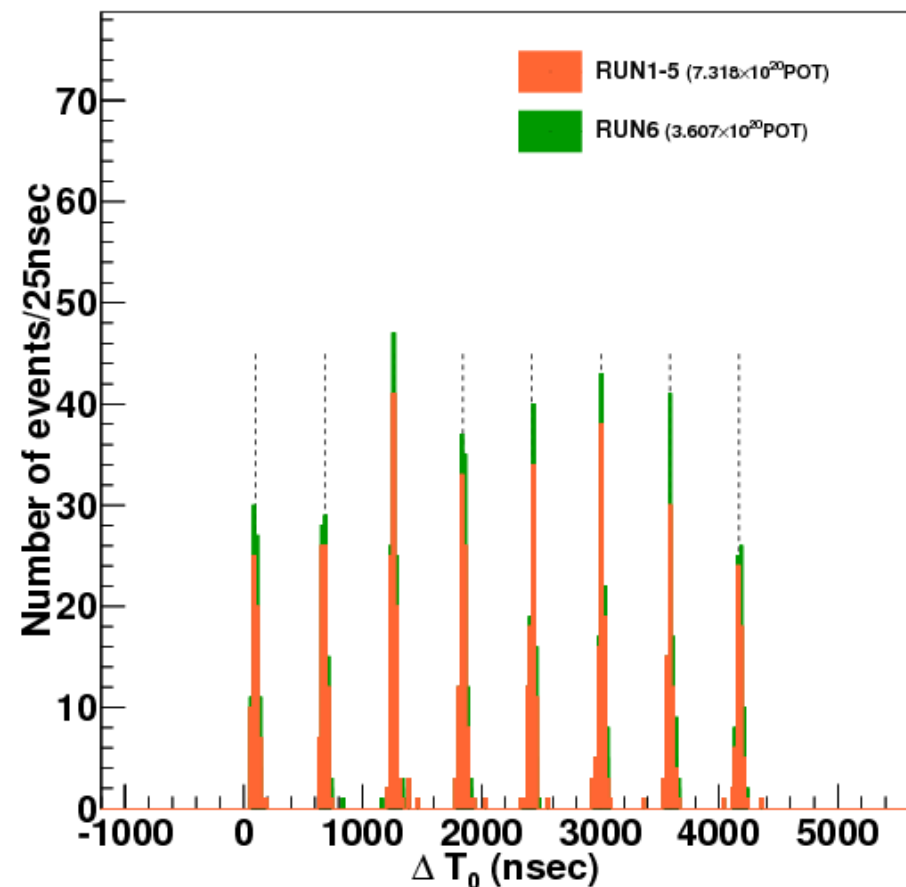
Fit external data (MiniBooNE, MINERvA) to suite of available models:

- Neutrino and antineutrino datasets fit to determine RPA correction choice and uncertainties on MAQE



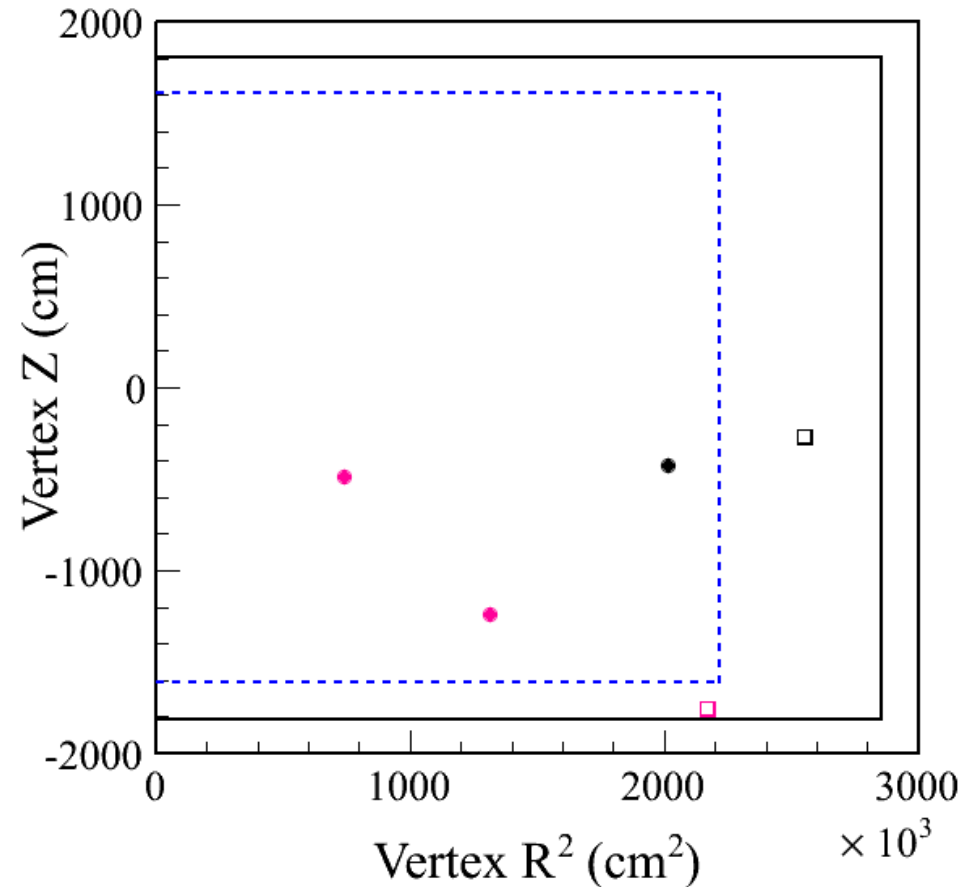
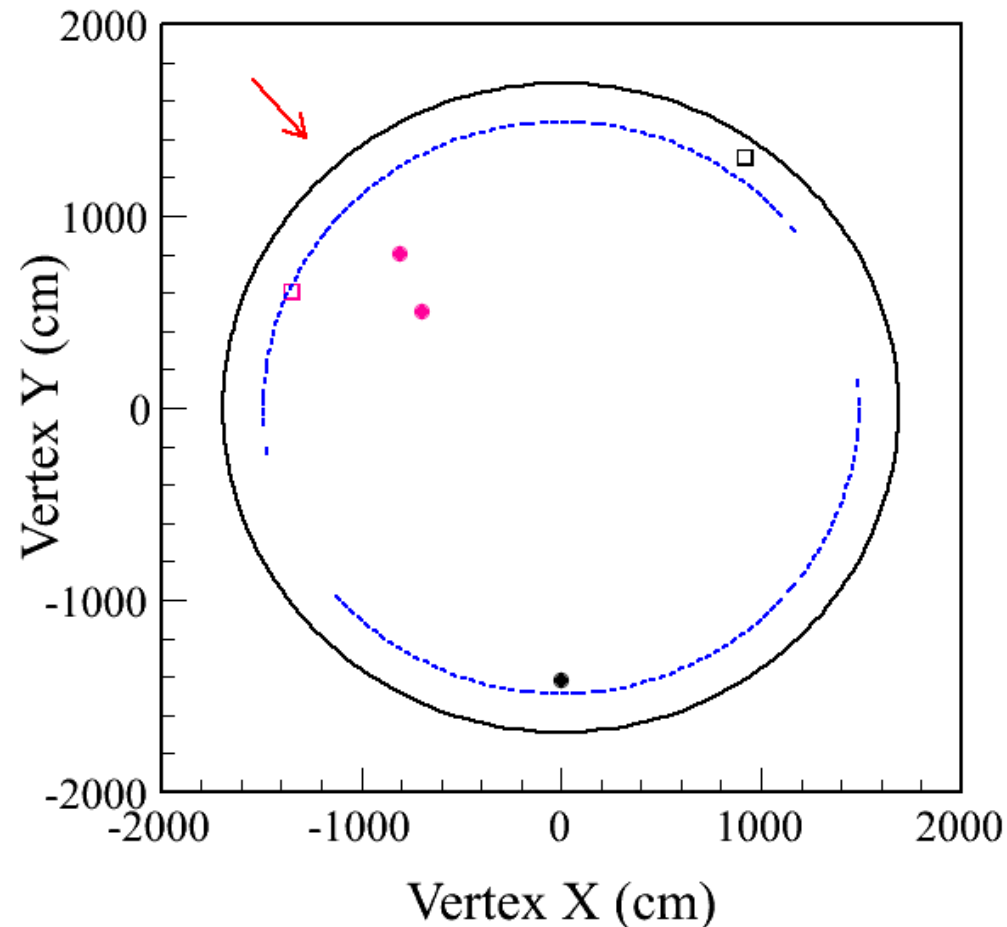
Hope was that Nieves et al model would resolve high MAQE for MiniBooNE. Instead:

- Forward scattering region for MiniBooNE neutrino model doesn't fit well
- Low Q^2 MINERvA nu/nubar disfavors Nieves RPA, suppresses MEC
- MINERvA data are 20% lower than MiniBooNE.
- For now: uncertainties inflated to cover disagreement between datasets
- Next: improve inputs: covariance from MiniBooNE, revisit model parameterization



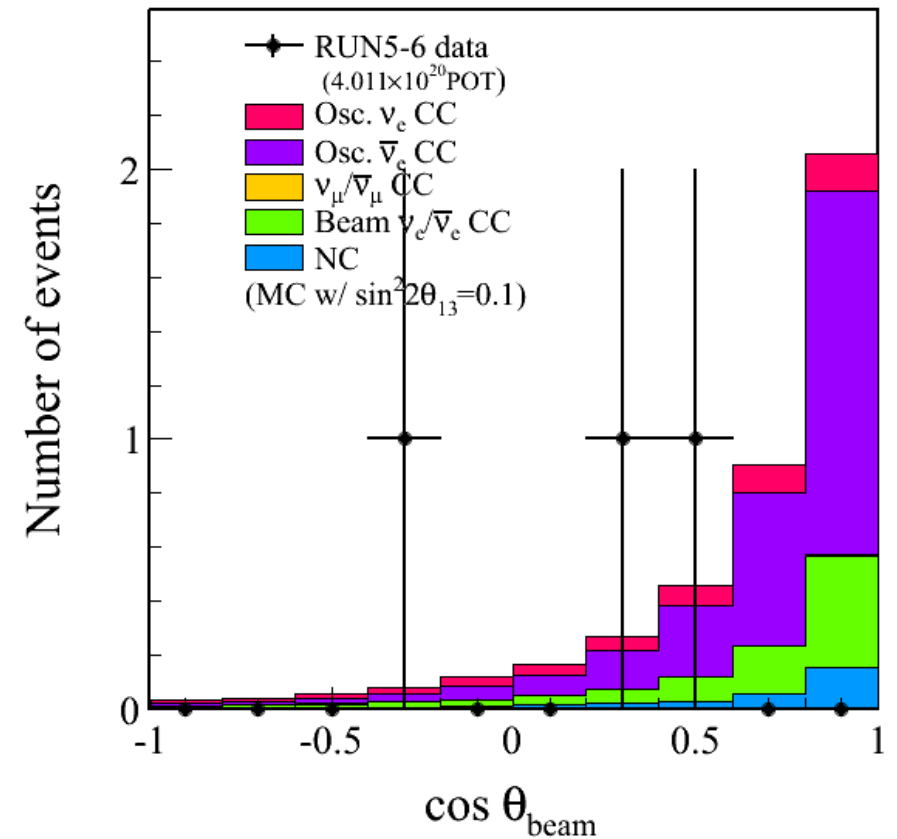
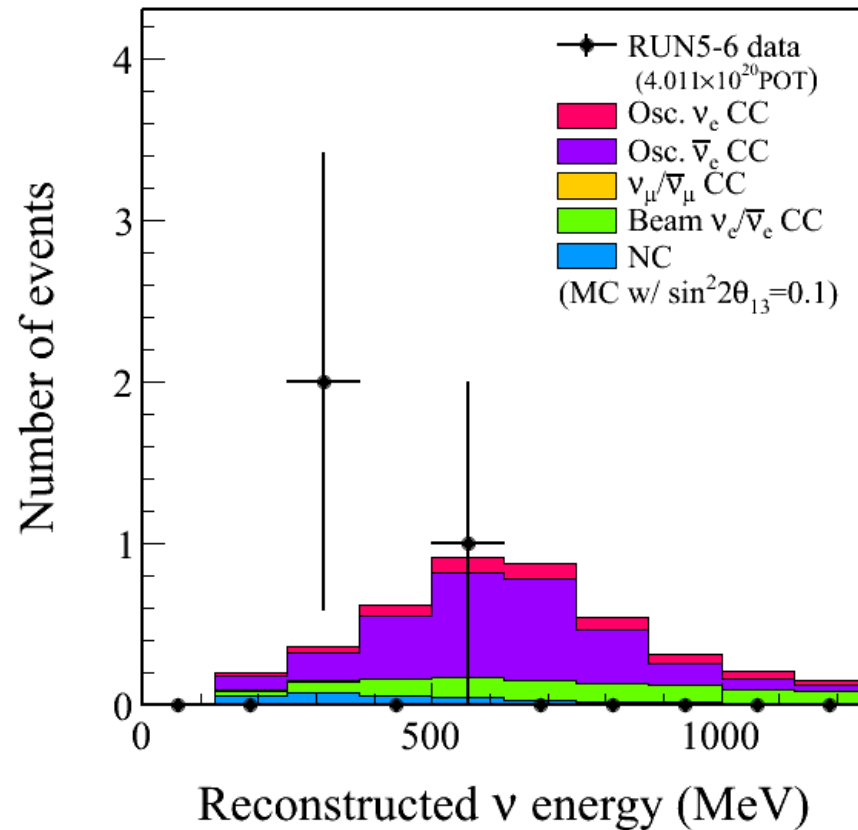
dT0 distribution of all the FC events (zoomed into the spill on-timing window) observed during Run1-5 (orange) and Run6 (green). The eight dotted vertical lines represent the 581 nsec-interval bunch center positions fitted to the observed FC event times albeit with their spacing preserved. The two histograms are stacked.

Antielectron neutrino candidates distributions

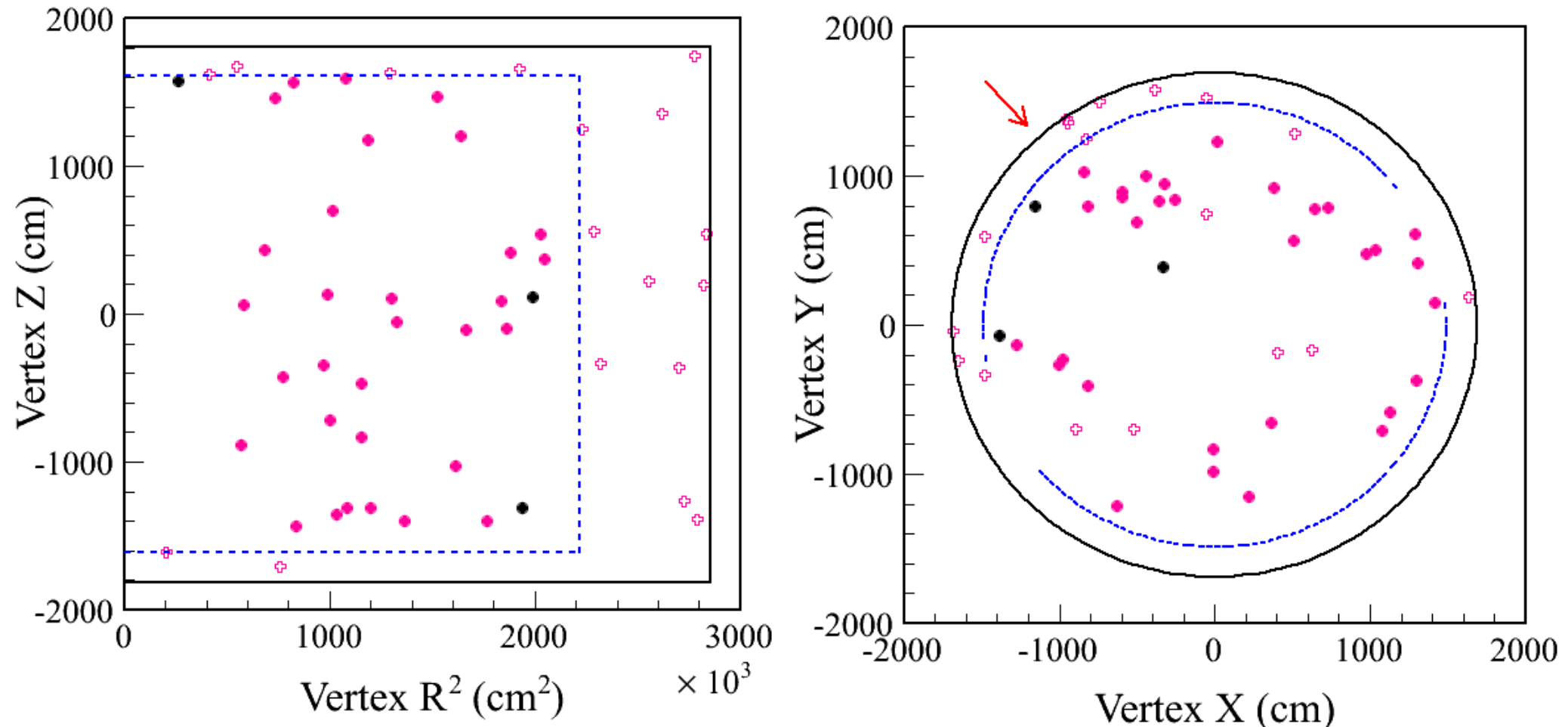


Two-dimensional R^2 -Z distribution of the reconstructed vertex position of the anti- ν_e candidate events. Dashed blue line indicates the fiducial volume boundary. Black markers are events observed during RUN5, and pink markers are events from RUN6. Hollow crosses represent events passing the anti- ν_μ selection cuts other than the fiducial volume cut.

Antielectron neutrino candidates distributions

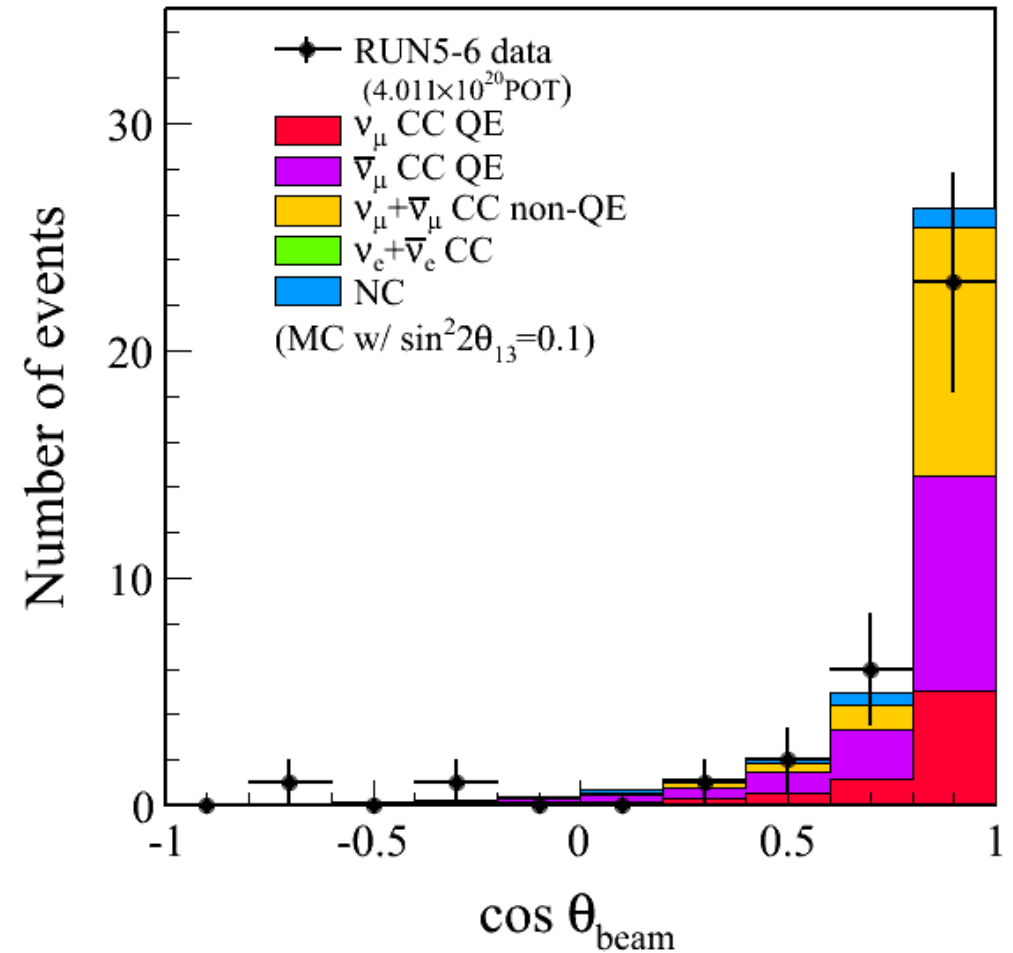
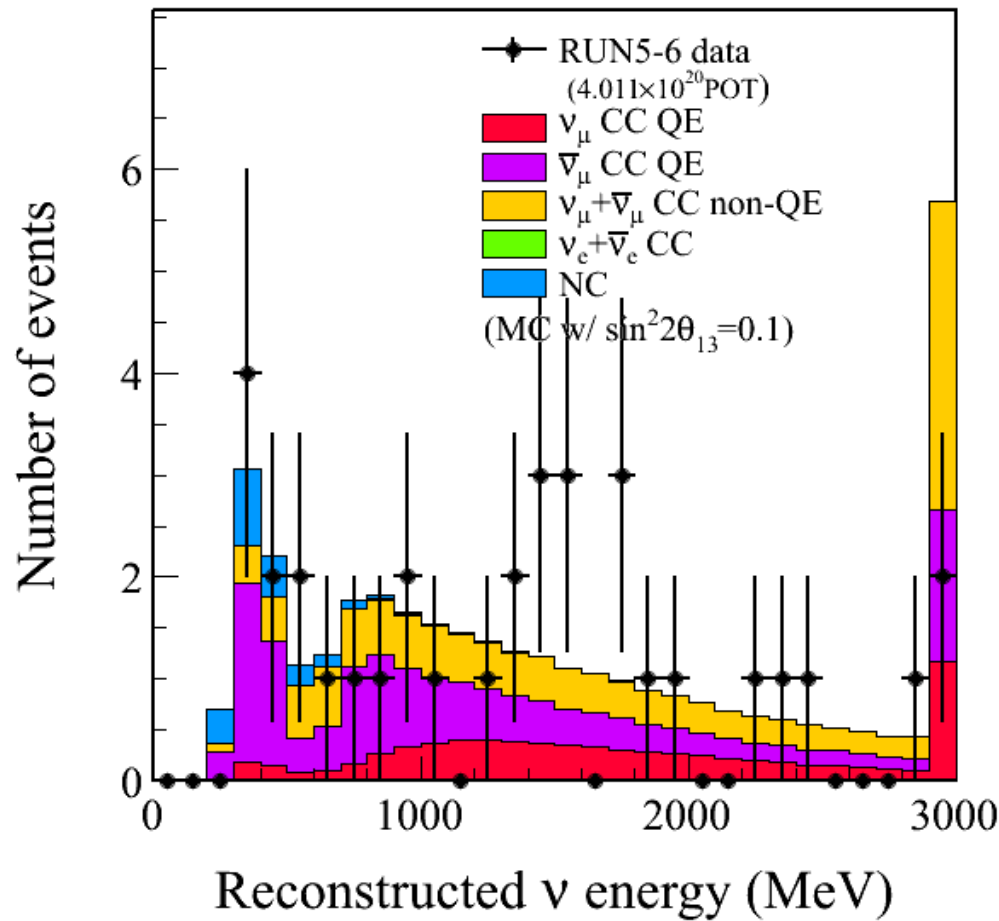


Antimuon neutrino candidates distributions



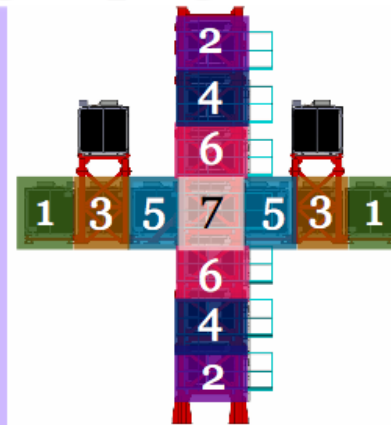
Two-dimensional R^2 - Z distribution of the reconstructed vertex position of the anti- ν_μ candidate events. Dashed blue line indicates the fiducial volume boundary. Black markers are events observed during RUN5, and pink markers are events from RUN6. Hollow crosses represent events passing the anti- ν_μ selection cuts other than the fiducial volume cut.

Antimuon neutrino candidates distributions

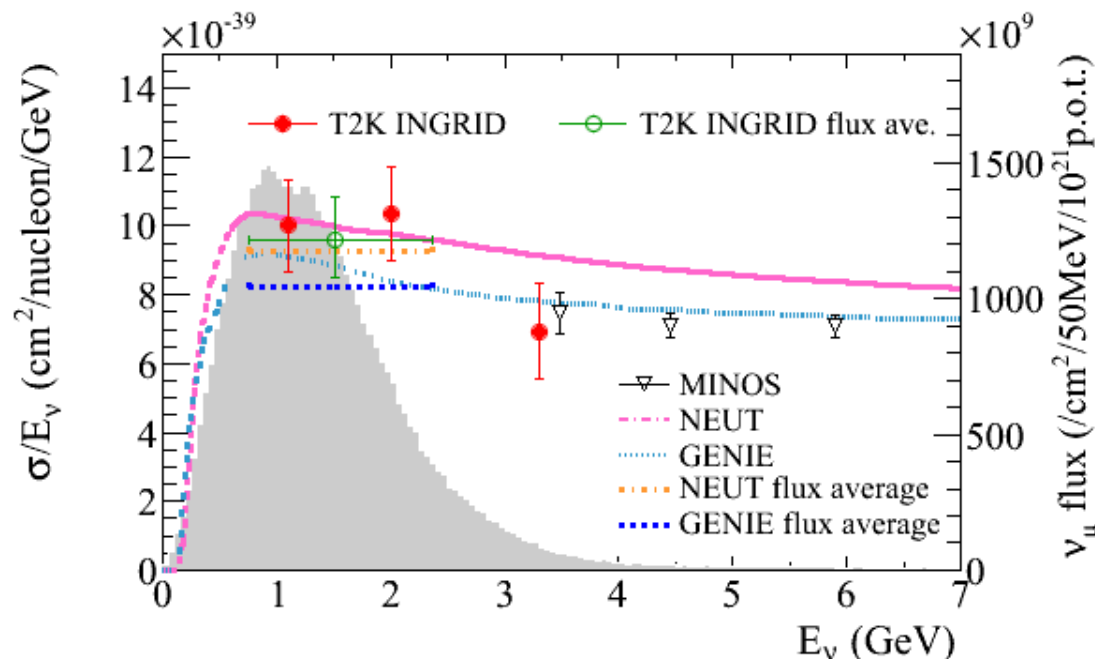
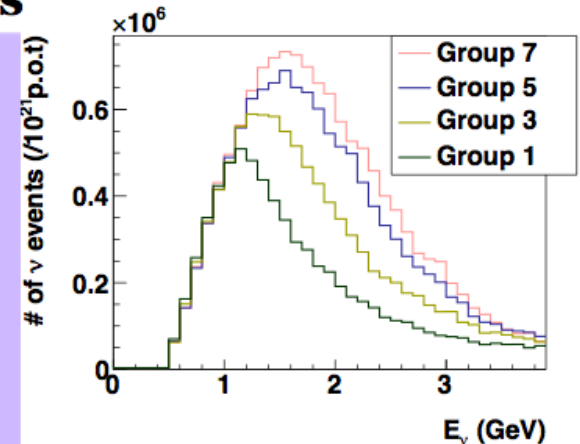


- Utilize # of event at different modules
 - Different energy spectra at different modules because of different off-axis angles ($\theta_{OA}=0-0.9^\circ$)
- Group two modules to minimize effects from the variation of the neutrino beam direction
 - 14 modules \rightarrow 7 groups

Definition of grouping modules



Energy spectra predicted by MC



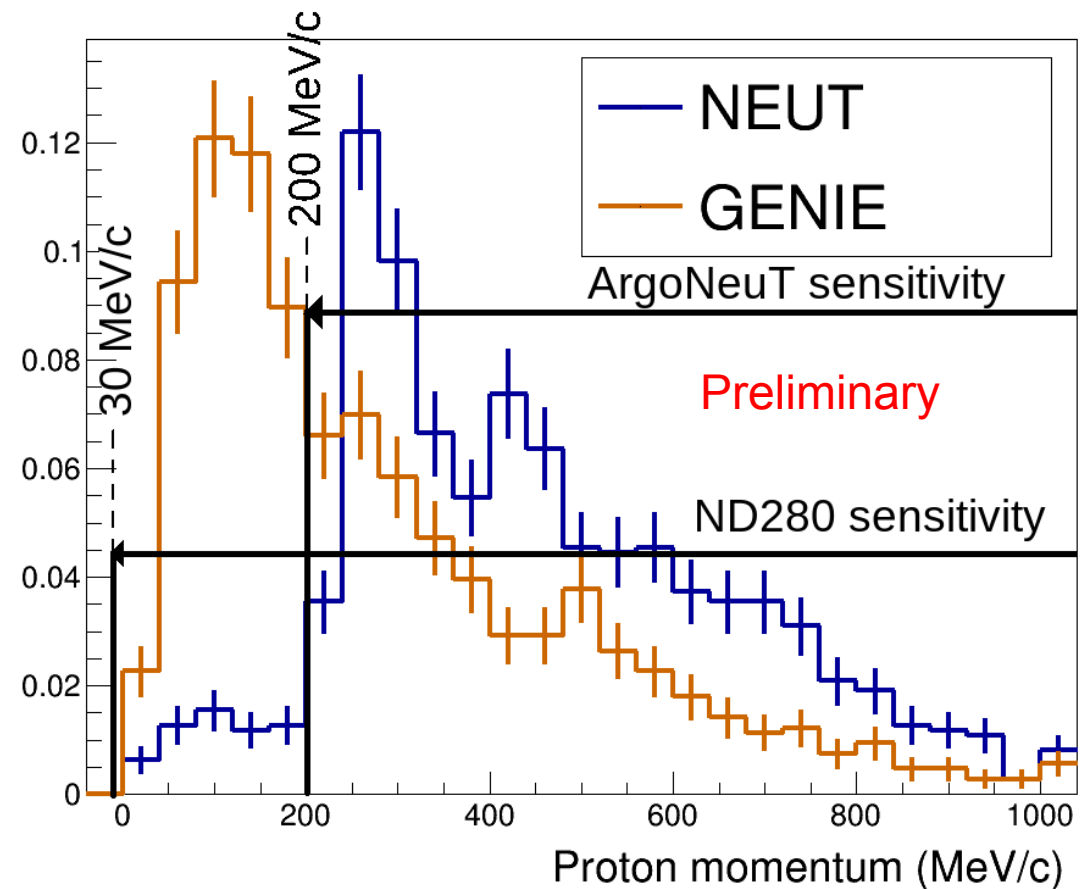
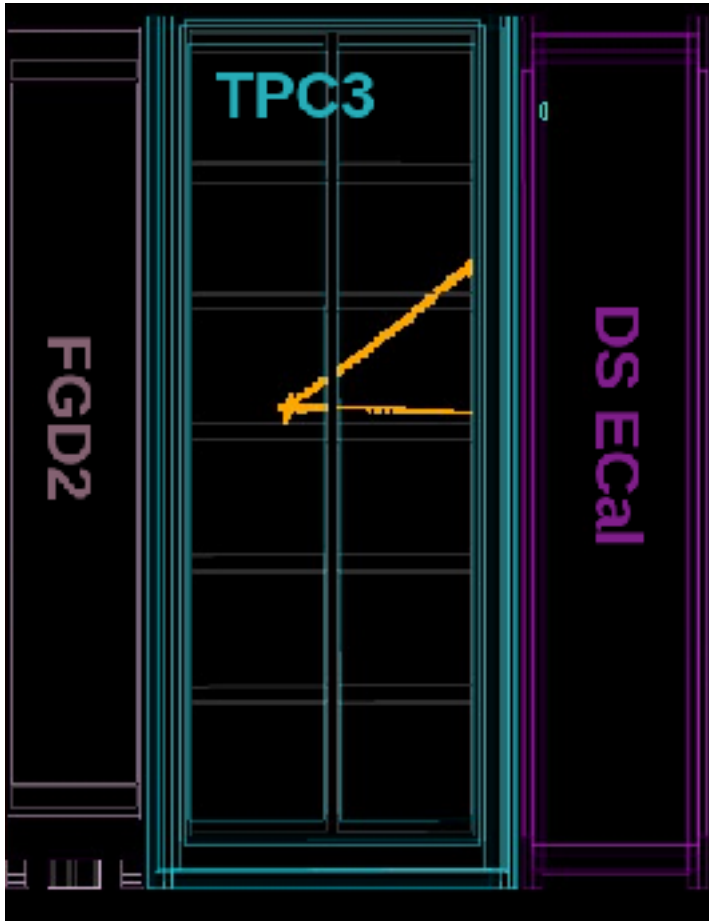
Compare nearby CC inclusive event rate across the on-axis (INGRID) detector:

- Target material: Fe
- Flux varies across detector due to off-axis effect
- Infer energy dependence from variation

Cross section tuning from near detector fit

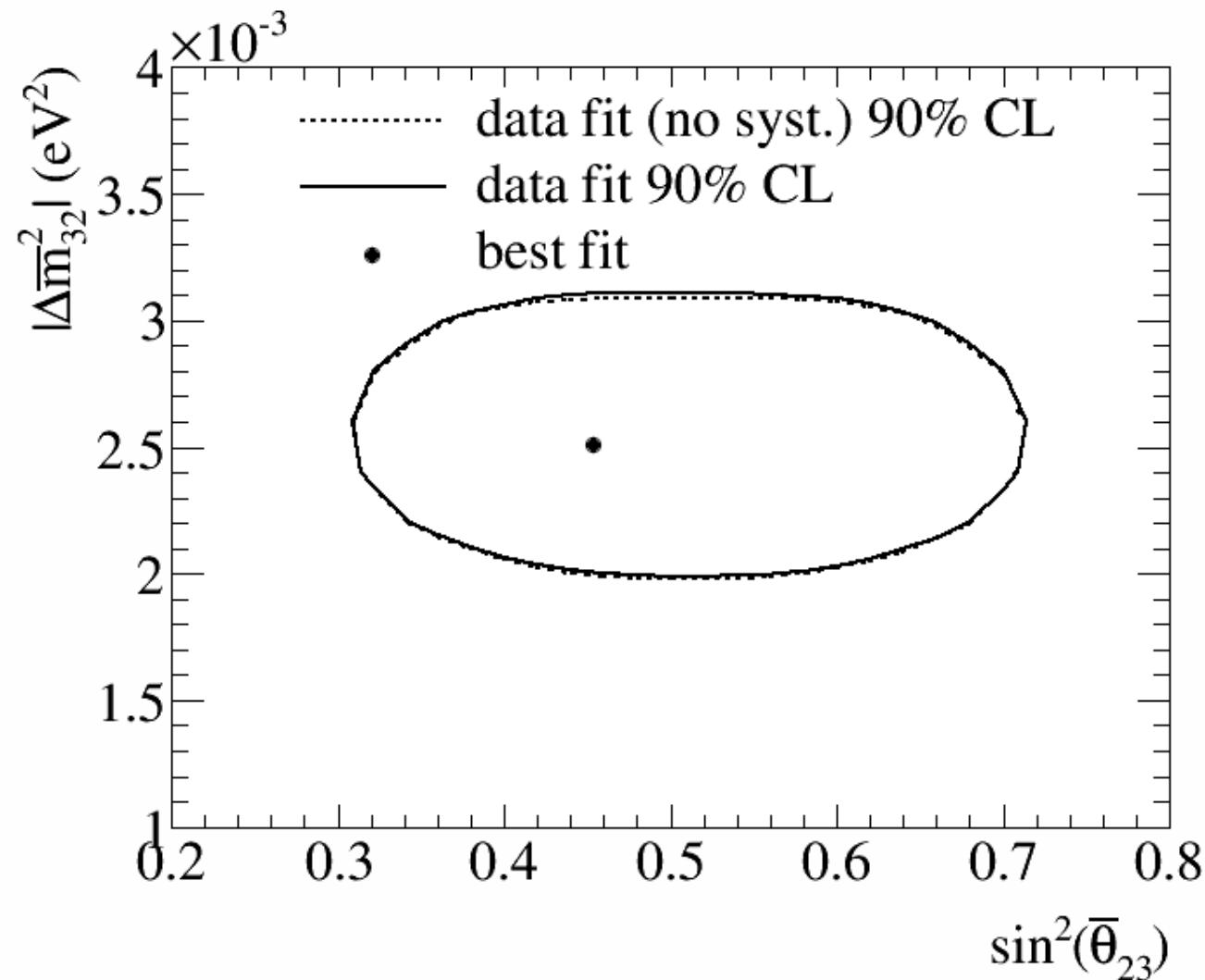
M_A^{QE} (GeV/ c^2)	1.15 ± 0.069607	1.1371 ± 0.033559
p_F ^{12}C (MeV/ c)	223.0 ± 12.301	222.67 ± 8.8333
MEC ^{12}C	27.0 ± 29.053	103.11 ± 17.245
E_B ^{12}C (MeV)	25.0 ± 9.0	23.903 ± 7.3458
p_F ^{16}O (MeV/ c)	225.0 ± 12.301	224.43 ± 12.152
MEC ^{16}O	27.0 ± 104.13	103.1 ± 101.49
E_B ^{16}O (MeV)	27.0 ± 9.0	27.045 ± 8.8047
$CA5^{RES}$	1.01 ± 0.12	0.86234 ± 0.074094
M_A^{RES} (GeV/ c^2)	0.95 ± 0.15	0.72437 ± 0.052156
Isospin= $\frac{1}{2}$ Background	1.3 ± 0.2	1.4853 ± 0.19014
ν_e/ν_μ	1.0 ± 0.02	1.0008 ± 0.019997
CC Other Shape	0.0 ± 0.4	0.023024 ± 0.1928
CC Coh ^{12}C	1.0 ± 1.0	0.021658 ± 0.16037
CC Coh ^{16}O	1.0 ± 1.0	1.0764 ± 0.97171
NC Coh	1.0 ± 0.3	0.98 ± 0.29922
NC Other	1.0 ± 0.3	1.4128 ± 0.1858

T2K as a cross section experiment



Gaseous TPCs (3 in total) are predominantly Ar gas:

- Proton threshold is lower than LAr
- New reconstruction, search underway for such events...

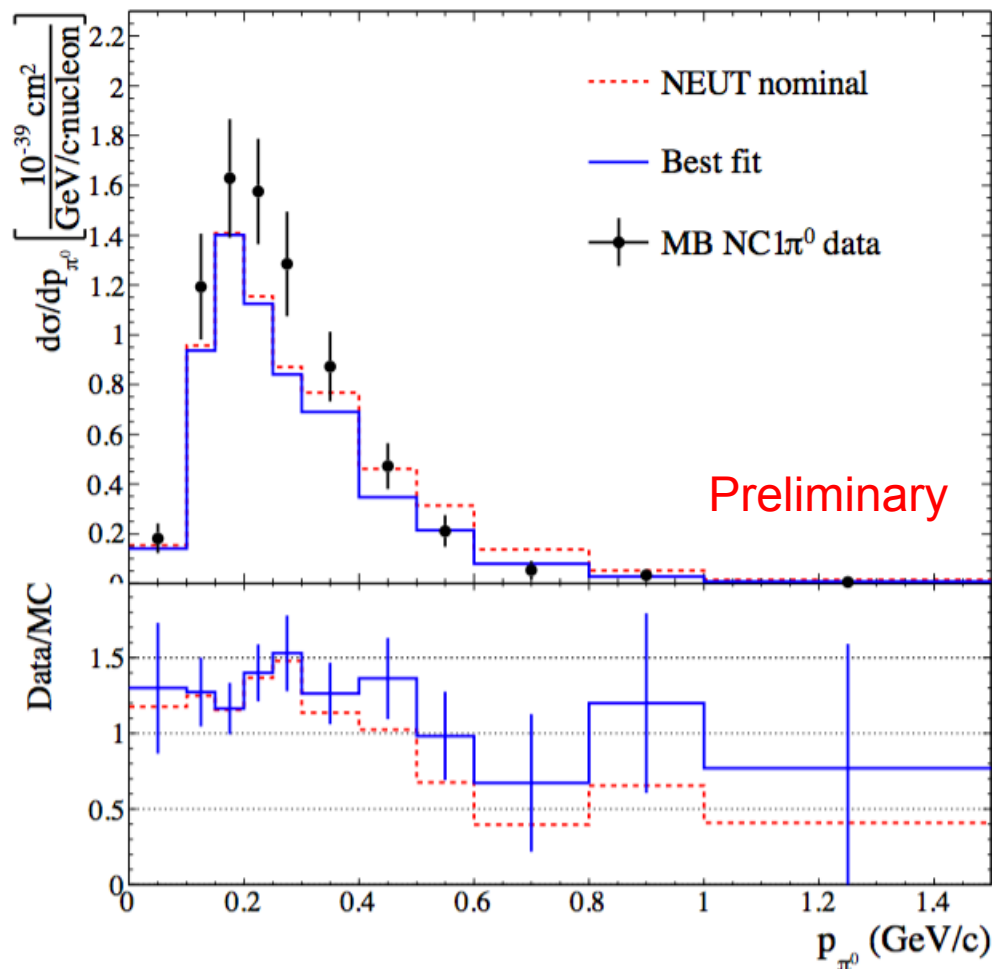


Our antineutrino measurements are statistics limited

- Analysis with and without systematics included barely changes the contours

Incomplete parameterization, difficult to reproduce rate, shape of pions

- π^0 spectrum for MiniBooNE NC π^0 is harder than NEUT, NUANCE
- Added empirical parameter to alter relative contribution of high W to low W contributions. Disagreement could also be due to in-medium treatment

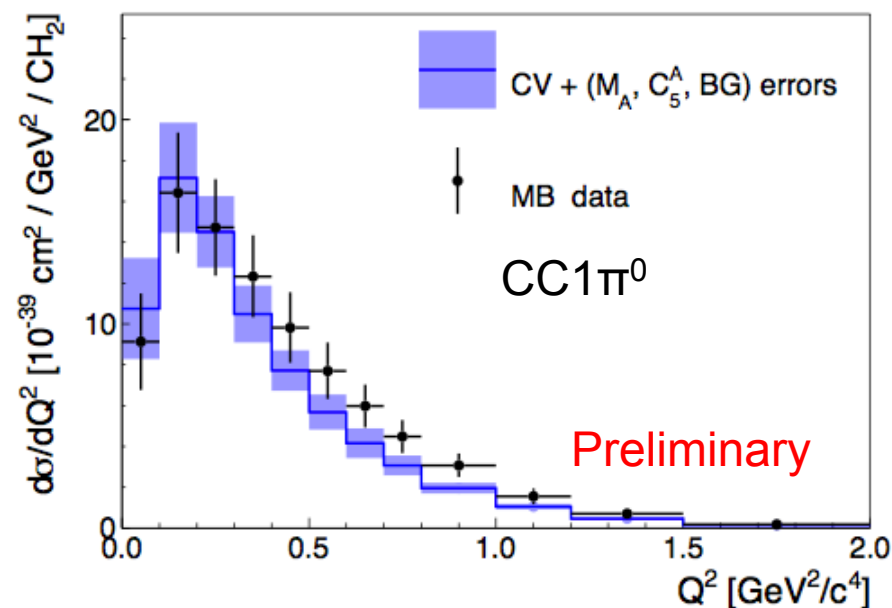
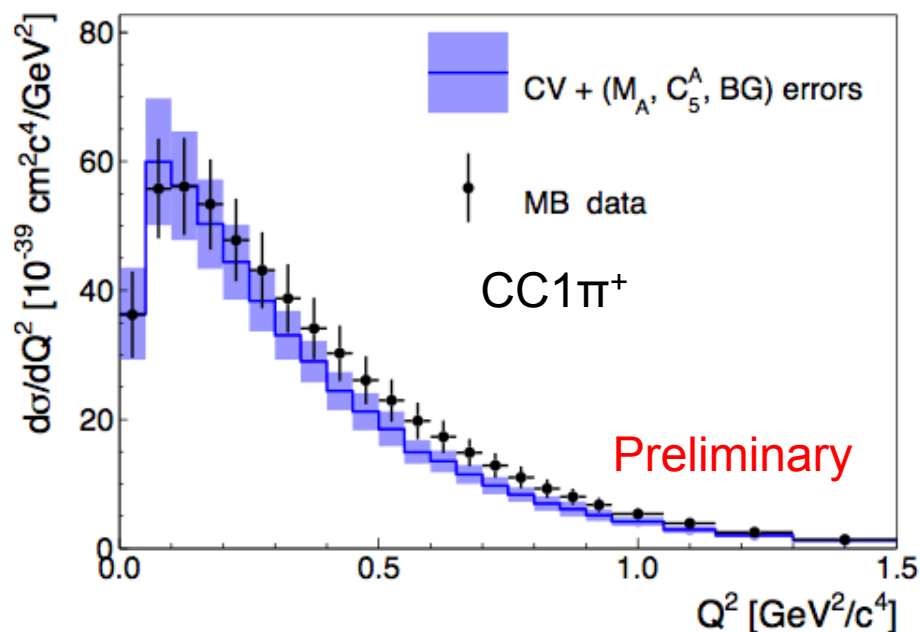


2015: Updated RS form factors from K. M. Graczyk and J. T. Sobczyk. Phys. Rev. D, 77:053001 (2008)

Fit neutrino deuterium channels:

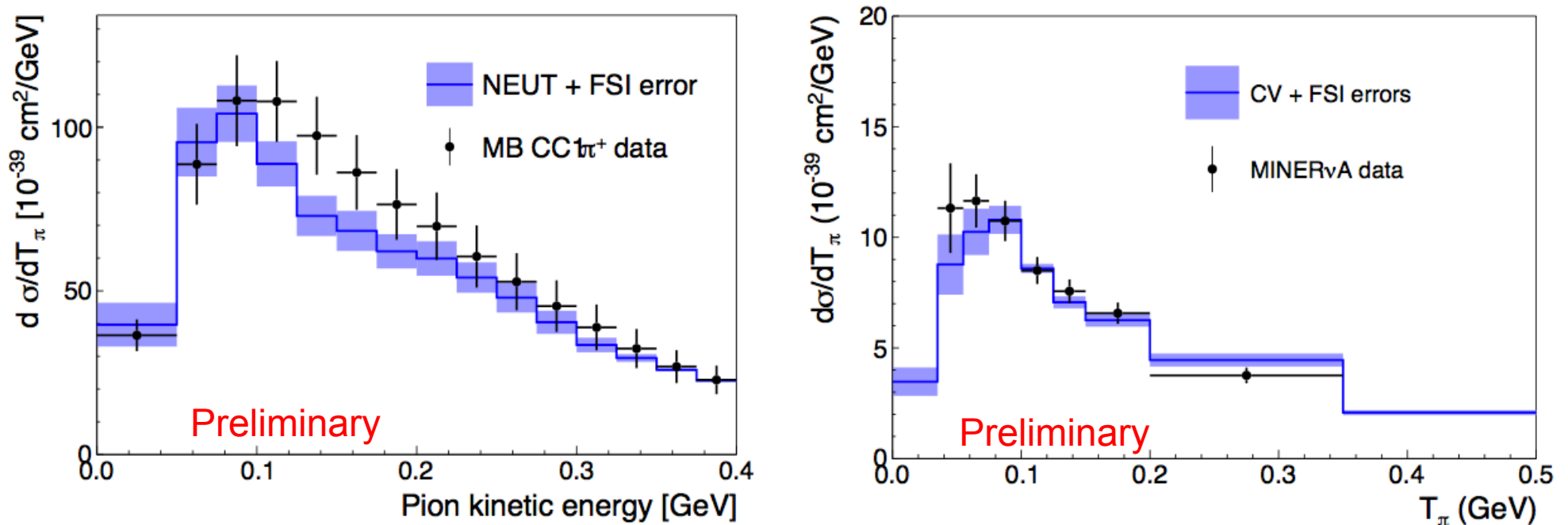
- $C_5^A(0)$ driven by ANL/BNL disagreement
- MARES (axial form factor mass)
- Non-resonant background scale factor

- Reasonable agreement Q^2 (and reco. E assuming pion)
- Fixing remaining difference in Q^2 doesn't resolve other kinematic variable differences, such as pion momentum (pion angle OK)



- Fitting MiniBooNE data is possible, but requires significant suppression of absorption
- Need to revisit FSI + in medium treatment

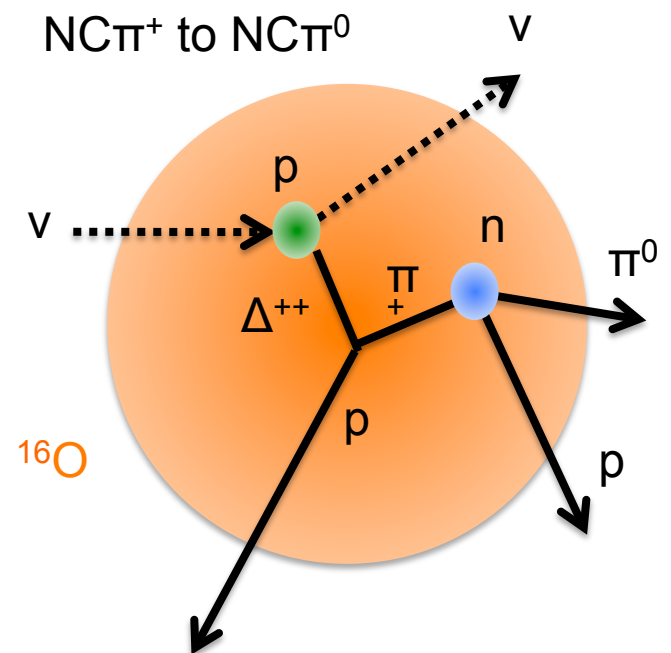
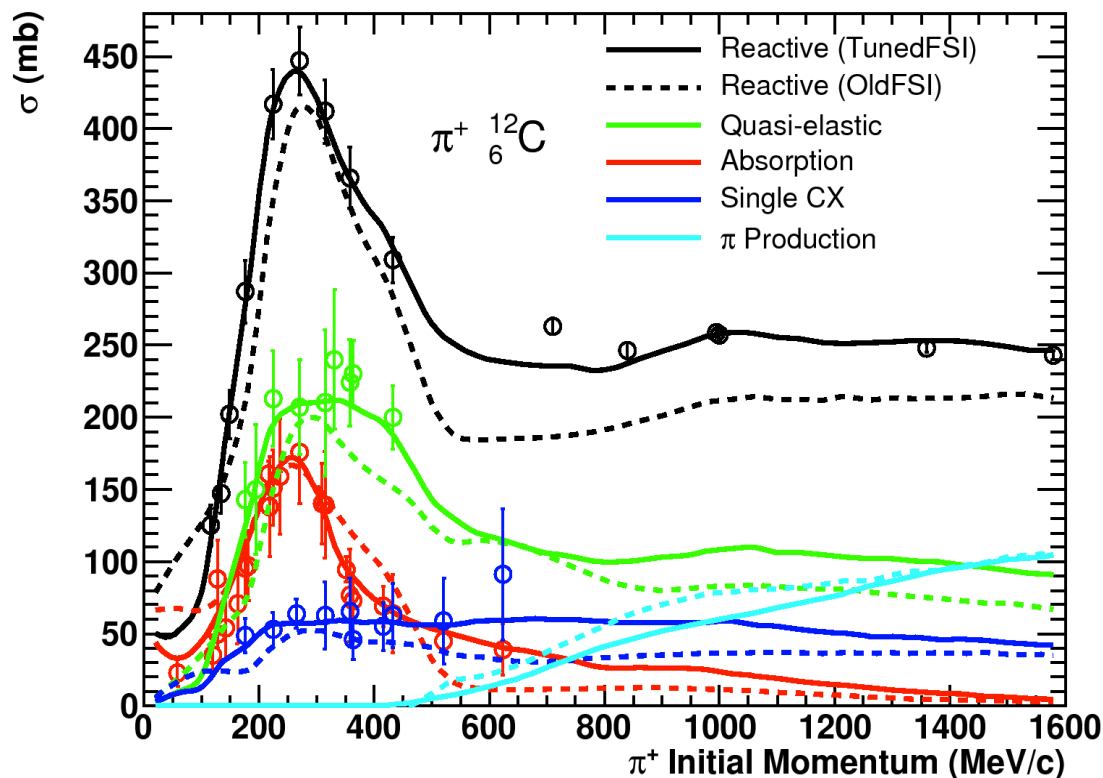
Shape-only plots, also overall rate difference between the two experiments



New T2K near detector measurements of pion production coming soon

NEUT FSI model is a cascade model tuned on “free-range” $\pi+N$ data

- ~3% error in disappearance analysis at far detector
- New data (DUET) and consideration of correlations between points
- Do we represent angular distributions of scattered pions?
- Model uncertainty: Would GiBUU (transport model) give a different answer?
- Relationship to Enu: Are models representative of $\Delta \rightarrow \pi$ in medium?
 - Data Mining collaboration for comparable Q^2 as neutrino probe

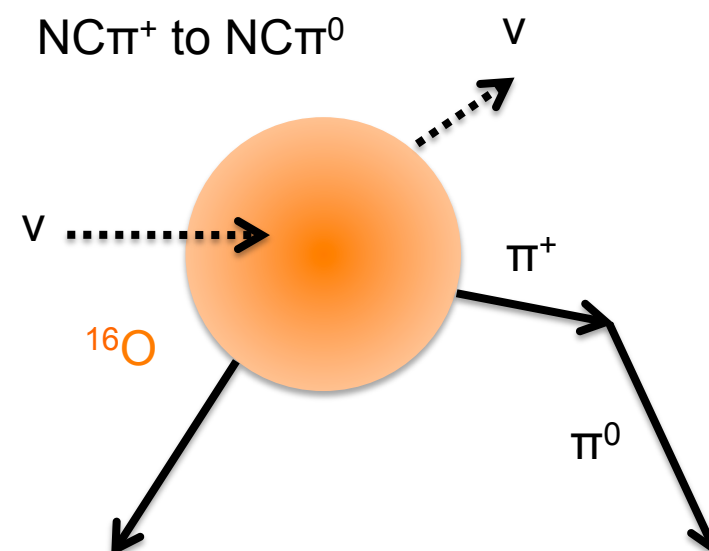


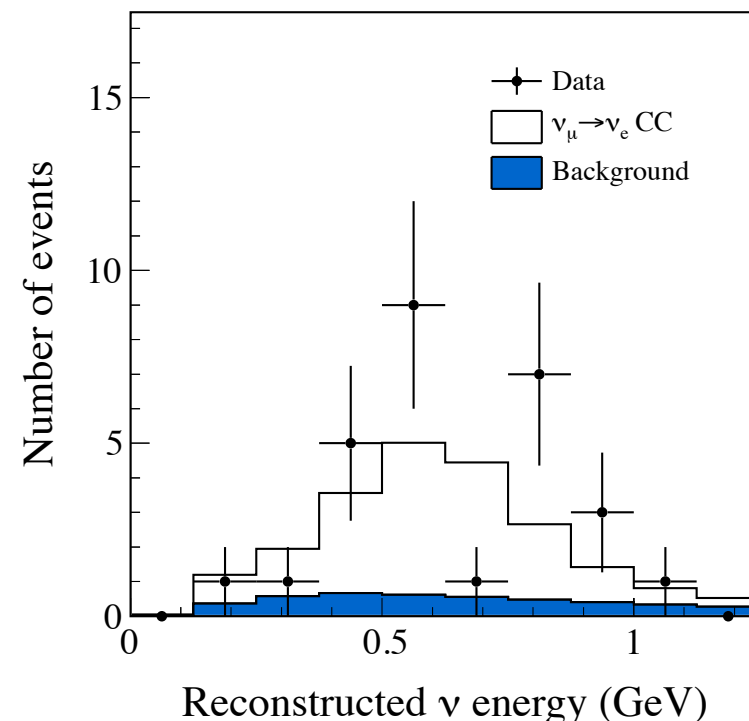
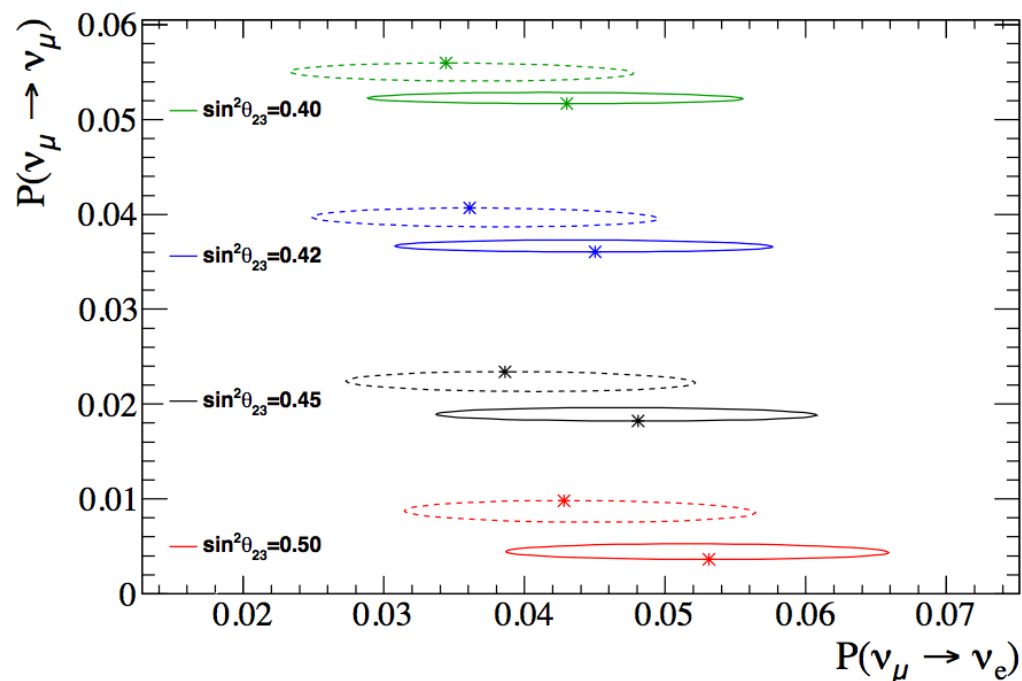
Pion scattering in the detector is a background to cross section understanding of what comes out of the nucleus (“secondary interactions”)

- Consistent treatment within same model at far detector
- Significant detector uncertainty for near detectors; LArIAT important for DUNE

TABLE XI: Minimum and maximum fractional errors among all the $(p_\mu, \cos \theta_\mu)$ bins, including the largest error sources. The last column shows the fractional error on the total number of events, taking into account the correlations between the $(p_\mu, \cos \theta_\mu)$ bins.

Systematic error	Error Size (%)	
	Minimum and maximum fractional error	Total fractional error
B-Field Distortions	0.3 - 6.9	0.3
Momentum Scale	0.1 - 2.1	0.1
Out of FV	0 - 8.9	1.6
Pion Interactions	0.5 - 4.7	0.5
All Others	1.2 - 3.4	0.4
Total	2.1 - 9.7	2.5



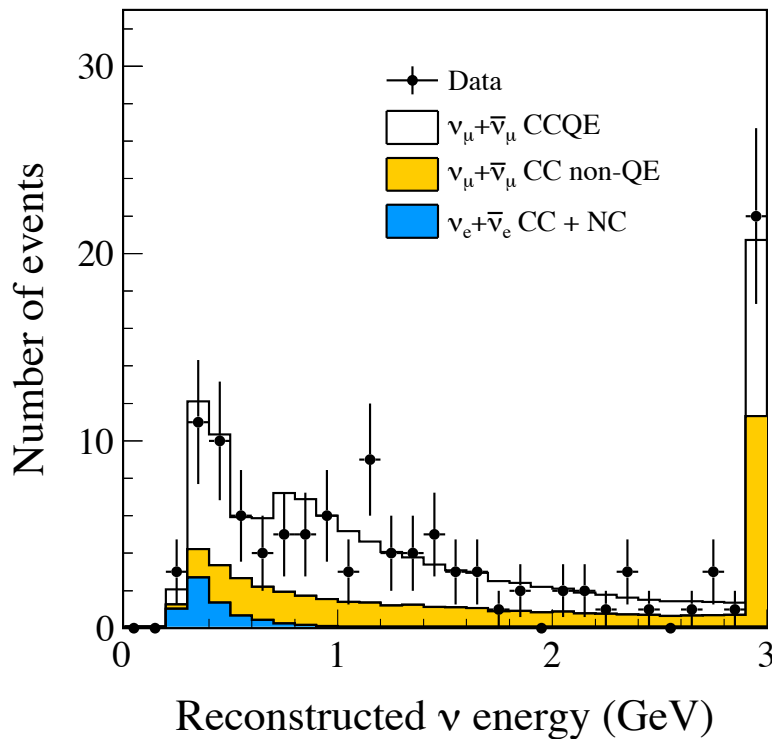


T2K collab, arxiv:1502.01550v1,
PRD 91, 072010 (2015)

First observation of CC ν_e appearance with 28 candidate events
(Phys. Rev. Lett. 112, 061802 (2014))

- Transition depends on all mixing parameters (Δm^2_{32} , θ_{23} , θ_{13} , δ_{CP} , mass hierarchy and Δm^2_{21} , θ_{12})

T2K results: disappearance

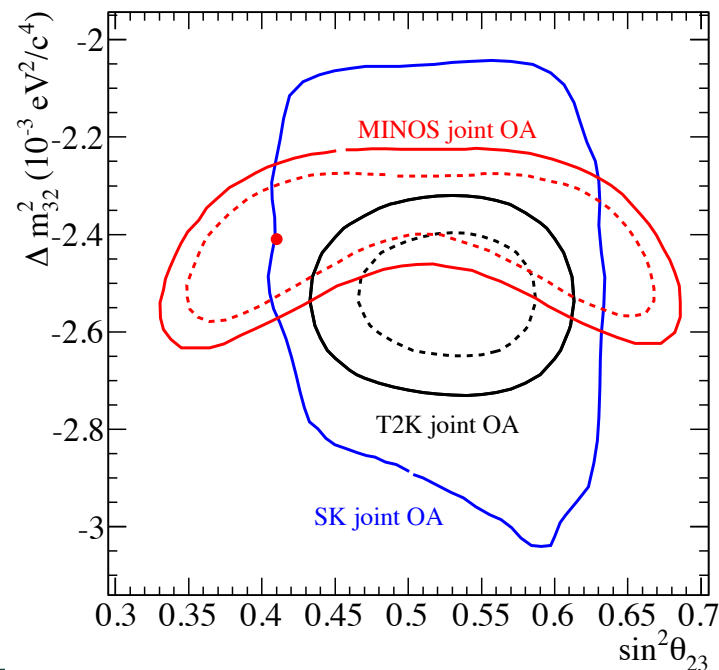
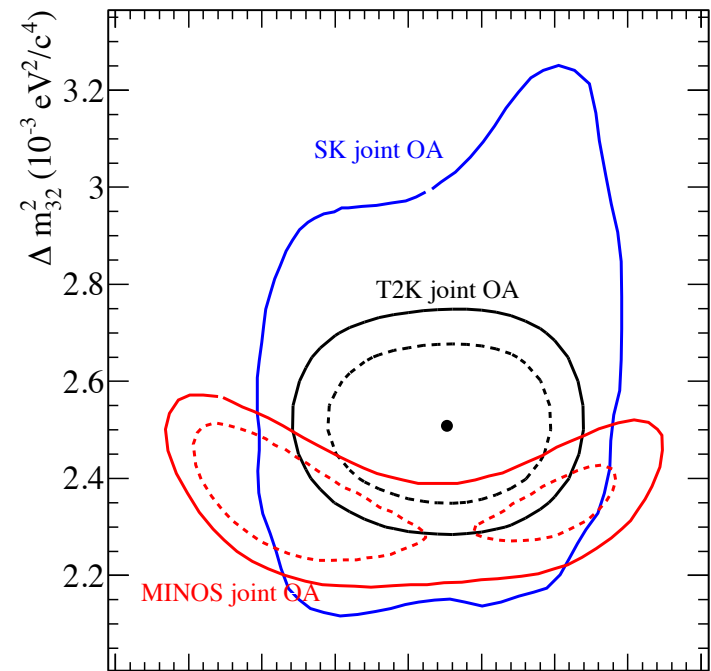


120 candidate ν_μ events observed

- Determine Δm_{32}^2 , $\sin^2 \theta_{23}$ from distortion to neutrino energy spectrum (PRL 112, 181801 (2014))

T2K data favors maximal disappearance

- Provides best constraint on θ_{23} to date, consistent with maximal (45°) mixing



T2K collab, arxiv:1502.01550v1, submitted to PRD

True	Fitted	$\theta_{23,min}$	$\Delta m_{31,min}^2 [eV^2]$	χ_{min}^2	σ_a	Fig. no.
GENIE (^{16}O)	GENIE (^{12}C)	44°	2.49×10^{-3}	2.28	–	4
GiBUU (^{16}O)	GENIE (^{16}O)	41.75°	2.69×10^{-3}	47.64	–	5(a)
		47°	2.55×10^{-3}	20.95	5%	5(b)
GiBUU (^{16}O)	GiBUU (^{16}O) w/o MEC	42.5°	2.44×10^{-3}	22.38	–	6(a)
GENIE (^{16}O)	GENIE (^{16}O) w/o MEC	44.5°	2.36×10^{-3}	19.54	–	6(b)

Significant variations to determination of θ_{23} , Δm_{32}^2 if a different simulation is used to generate fake data and fit (Coloma et al, PRD 89, 073015 (2014))

- Significant bias if multinucleon (MEC) component is not considered

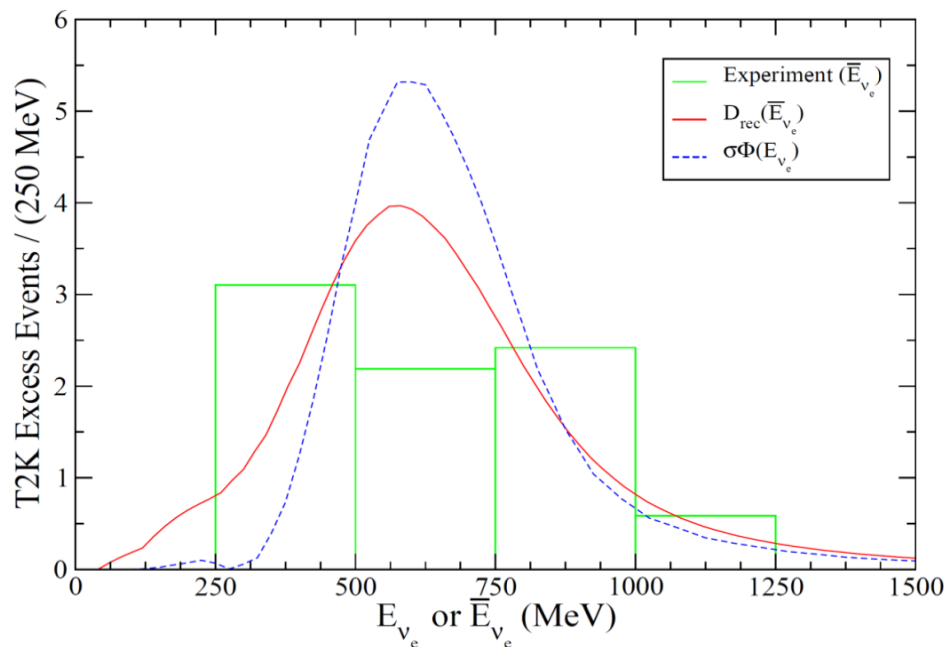
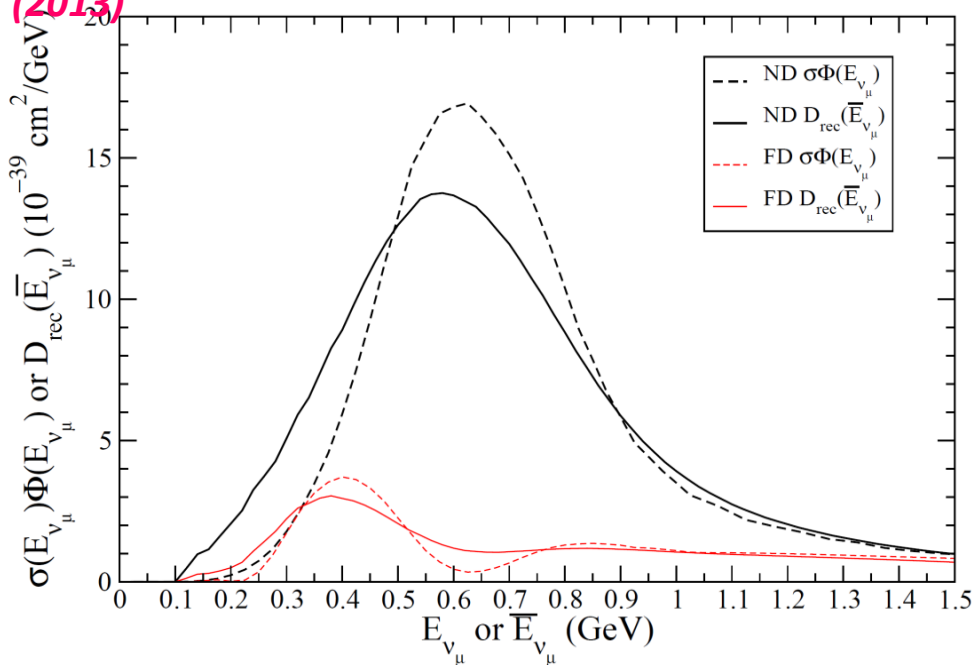
Also noted in theoretical publications discussing multinucleon effects, including:

- J. Nieves et al PRD 85, 113008 (2012)
- O. Lalakulich, U. Mosel, and K. Gallmeister, PRC 86, 054606 (2012)
- M. Martini, M. Ericson, and G. Chanfray, PRD 85, 093012 (2012)
- M. Martini, M. Ericson, and G. Chanfray, PRD 87, 013009 (2013)
- D. Meloni and M. Martini, PLB 716, 186 (2012)

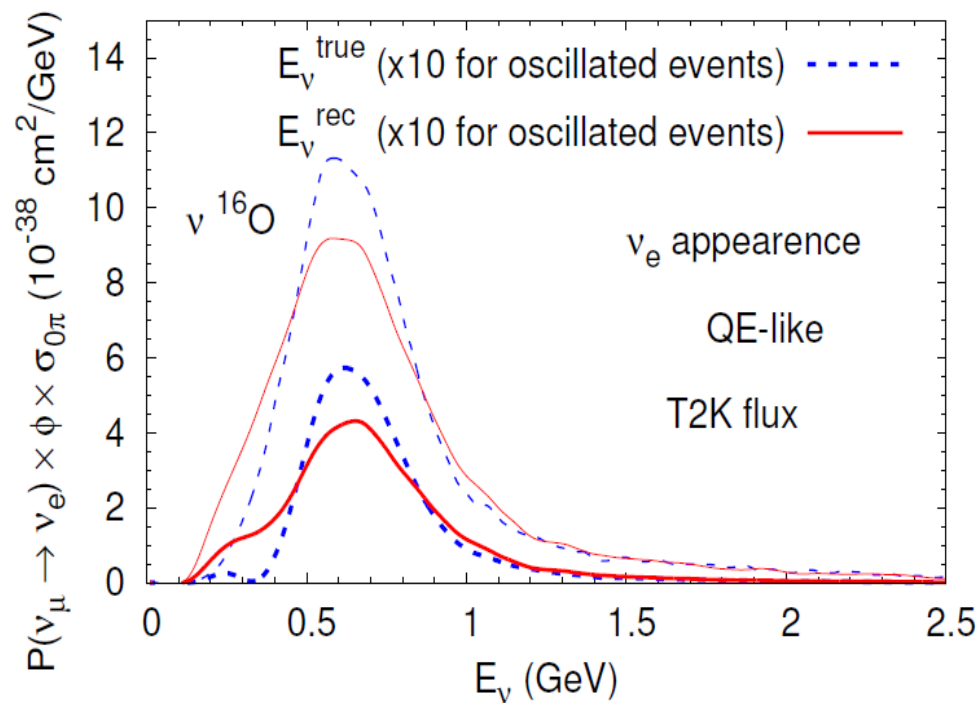
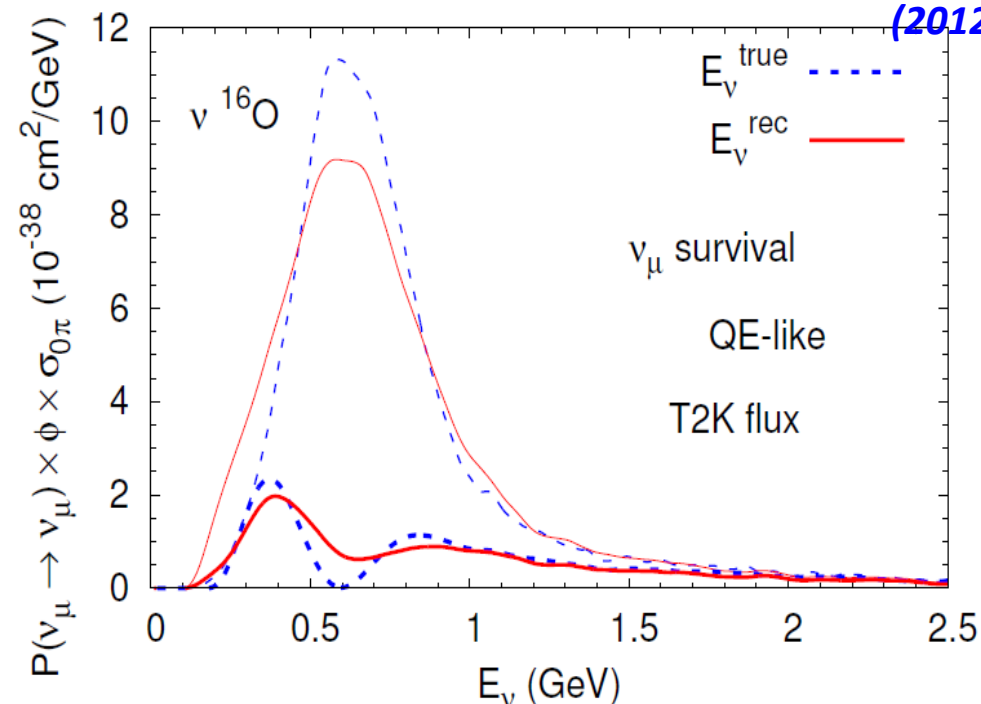
	$\sin^2 2\theta_{13}$	$\theta_{23}(^\circ)$	$\Delta m_{atm}^2 (10^{-3} eV^2)$
FG	[0.041-0.211] (0.105)	[40.1-51.3] (47.6)	[2.45-2.67] (2.56)
MECM	[0.023-0.154] (0.092)	[41.1-49.9] (45.4)	[2.49-2.67] (2.60)

Table 5: 90% intervals for $\sin^2 2\theta_{13}$, θ_{23} and Δm_{atm}^2 , for the MECM and FG models in the case the current T2K statistics is increased by a factor of 10. In parenthesis, the best fit points.

(2013)



(2012)



ν_μ to ν_e appearance:

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \ll 1,$$

$$\Delta = \frac{\Delta m_{32}^2 L}{4E_\nu}$$

$$A = 2\sqrt{2}G_F N_e \frac{E_\nu}{\Delta m_{32}^2}$$

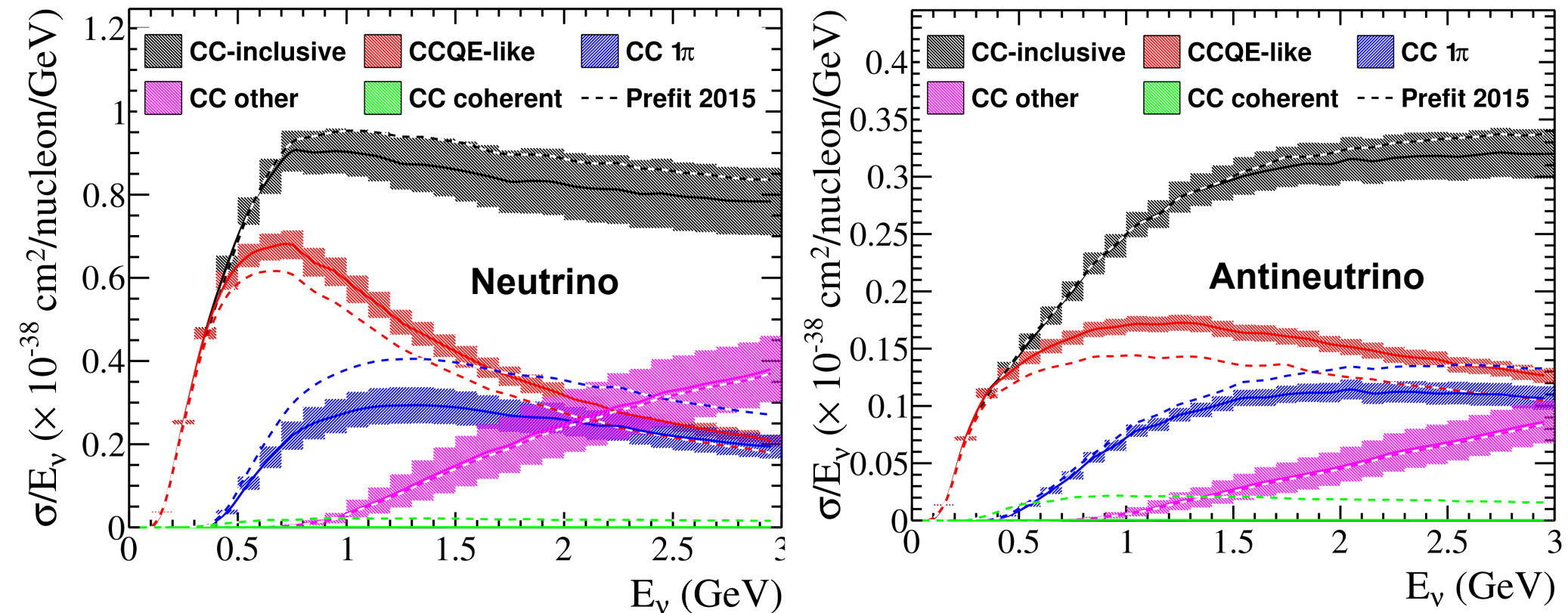
Approximation from
M. Freund, PRD 64, 053003

$$P_{\nu_\mu \rightarrow \nu_e} = \frac{1}{(A-1)^2} \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 [(A-1)\Delta] \\ - (+) \frac{\alpha}{A(1-A)} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\ \sin \delta_{CP} \sin \Delta \sin A\Delta \sin [(1-A)\Delta] \\ + \frac{\alpha}{A(1-A)} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \times \\ \cos \delta_{CP} \cos \Delta \sin A\Delta \sin [(1-A)\Delta] \\ + \frac{\alpha^2}{A^2} \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 A\Delta$$

Key players:

- $\Delta m_{32}^2 \sim 2.4 \times 10^{-3} \text{ eV}^2$ (atmospheric mass splitting), sign enters due to ν_e, ν_μ interactions in matter (matter effects, A terms)
- Mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP-violating phase δ_{CP}

Determine $\Delta m_{32}^2, \theta_{23}$ from measurements of ν_μ disappearance



NEUT model (5.3.2+) for 2015 (antineutrino, neutrino+antineutrino) analyses:

- Two new CCQE models implemented for consideration in the analysis:
 - CCQE: Spectral function model (Benhar et al.) $M_A^{\text{QE}} = 1.2 \text{ GeV}$
 - CCQE: Relativistic Fermi Gas (RFG)+Random Phase Approximation (RPA)
 - New: “Meson exchange current” (MEC) CCQE like scattering from Nieves et. al
- 1 π (NC and CC) production model: Rein-Sehgal with modified form factor for Delta. No pion-less delta decay.